Robotic Operations for the First Sample Depot on Mars

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***Abstract*—The Perseverance rover has completed a very successful 2.5 years on Mars. It has filled 24 of the 43 sample tubes it brought to Mars and completed the Three Forks Sample Depot on January 28, 2023, where it deposited 10 of these samples on the surface of Mars. Each deposited sample was sealed within a Returnable Sample Tube Assembly (RSTA) and attached glove assembly (RGA). Creation of this sample depot has satisfied all of the prime mission requirements. The Mars Sample Return mission aims to bring some of the samples that Perseverance collects from Mars to Earth, either via direct delivery from the Perseverance rover to the Sample Retrieval Lander (SRL), or by deploying Sample Recovery Helicopters (SRH) to fly to the samples and collect them. This paper describes the strategic planning and tactical execution of the mobility, robotic arm, sampling and imaging activities that led to the very successful depot creation. A number of factors had to be considered including SRH access, communication obstructions, view for imaging, and contingency handling. It discusses how the strategic planning arrived at the plan for alternating two main types of sols: drop and image, and drive and photoshoot. Drop and image choreographed moves between the Perseverance external robotic arm and the Adaptive Caching Assembly (ACA) inside the rover, which has a second robotic arm - the Sample Handling Arm - to image the sample before and after depositing it on the surface. Drive and photoshoot consists of backing up and taking mid-drive images of the dropped sample. During the 42 Martian days (sols) that it took to create and document the Three Forks depot, the rover drove 207.93 meters, dropped 10 sample RGAs, and took 4000 images. Completion of this sample depot ensures that there will be samples for the Mars Sample Return mission to transport back to Earth for the first time.**

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1. INTRODUCTION

The NASA Mars 2020 (M2020) Perseverance rover and Ingenuity helicopter landed in Jezero crater on February 18, 2021. The mission achieved its prime objective to select, document, core, and deploy a high-value sample collection on the surface of Mars within one Mars year of landing (one Mars year is 687 Earth days). The depot shown in Figure 1 contains a cache of 10 Martian samples, that may be the very first samples ever brought to Earth from another planet. Once back on Earth, the samples would undergo comprehensive analysis for generations to come, using sophisticated instruments and laboratories only available on Earth. This paper describes the robotics and imaging activities that led to this historic sample depot creation at Three Forks on Mars.

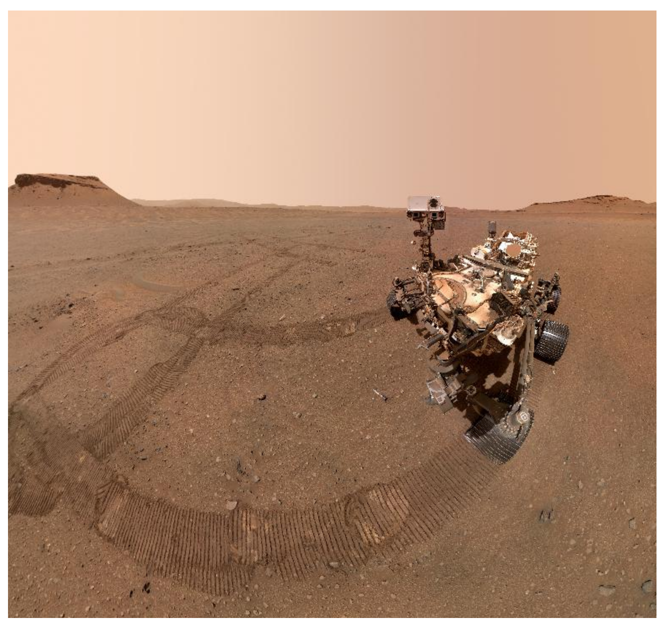

Figure 1. Perseverance next to the penultimate Atsah sample it deposited at the Three Forks sample depot, shown in this "selfie" mosaic comprised of dozens of WATSON images.

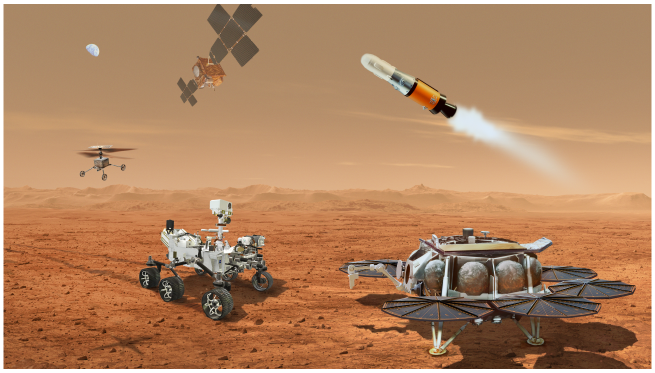

Figure 2. Artist's illustration of the spacecraft planned for the Mars Sample Return mission, as of October 2023.

The Mars 2020 mission with the Perseverance rover is a first step of a bigger vision to return samples from Mars to Earth. At the time of depot creation the international Mars Sample Return (MSR) partnership between NASA and the European Space Agency (ESA) was being planned with several spacecraft (shown in Figure 2), including a lander, rocket, and multiple helicopters, for delivering samples collected by Perseverance to Earth [1]. The decision to implement the MSR mission will not be finalized until NASA's completion of the National Environmental Policy Act (NEPA) process. This document is being made available for information purposes only.

2. WHY A SAMPLE DEPOT ON MARS?

Robotic explorers have done a remarkable job increasing our knowledge of the solar system and beyond. But when samples can be brought back, they can be studied in the most advanced laboratories on Earth, yielding even greater understanding. Past missions have brought back samples from the Moon [2] [3] [4], asteroids [5] [6], solar wind [7], comet tails [8] and more. But other than serendipitous meteorites [9], thus far no samples have been brought back to Earth from any other planet in the solar system. Sample return missions to Mars and its moons have been started in the past [10] [11] [12], but Mars 2020 is the first mission to successfully land and begin collecting samples. The overall Mars Sample Return mission architecture will provide a scientifically diverse set of samples from Mars that could be studied for decades. The first step of that plan is to collect interesting samples on Mars [13] [14].

All of NASA's Mars Rovers have lasted longer than their promised lifetimes: e.g., Opportunity lasted 15 years, and Curiosity is still actively operating in its 12^{th} year. But to address the possibility that Perseverance may no longer be capable of rendezvousing with the Mars Sample Return Sample Retrieval Lander (SRL) in the early 2030's, at the time of this writing MSR has two plans for delivering the Perseverance samples to Earth: SRL will collect samples either directly from Perseverance or via helicopters dropping them onto the nearby surface [1]. In more detail, these two strategies are:

Perseverance Direct—In the prime plan, SRL will land at a safe distance close to Perseverance, which would then drive up to it. The lander's robotic arm would collect up to a decade's worth of samples, one at a time, directly from Perseverance's Bit Carousel.

Sample Recovery Helicopters—SRL plans to carry two Sample Recovery Helicopters (SRHs) to Mars to enable sample recovery from the depot if needed. SRL would land a safe distance from the depot, and SRHs would fly back and forth to the depot, collecting one sample at a time and returning to the fixed lander to drop it nearby for the lander robotic arm to pick up from the surface.

Figure 3. This Navcam image taken by NASA's Perseverance rover on Sept. 7, 2021, PDT (Sept. 8, EDT), shows two holes where the rover's drill obtained a pair of chalk-size core samples at the feature named Rochette.

To support both collection strategies, during the first Martian year of Perseverance operations mission planners chose to collect twin samples at each location (as shown in Figure 3) [15]. One of each pair would eventually be deposited outside of the rover into a depot, and the other preserved onboard to join a larger set of samples to be collected over many more years of exploration. Should any problems arise that would prevent Perseverance from transferring its onboard samples, the presence of the depot enables the SRH fallback plan.

So a depot was established, dropping 10 of the 43 sample tubes onto a flat, easily accessed area. Perseverance will carry the remaining twin samples and will also fill the additional sample tubes over the coming years. MSR plans to select between these two sample collection strategies when it is closer to landing on Mars in the early 2030s.

3. REQUIREMENTS

Once the criteria for the sample cache terrain had been established, the MSR team identified and down-selected several candidate sample depot sites along the planned Perseverance traverse path using orbital imagery. Arrival at one of these, the area that eventually became known as Three Forks, coincided with the end of a 31-sol period of operations dedicated to moving the rover as quickly as possible to terrain near the Jezero Delta region. It was during the final "Rapid Traverse" drive [16] on sol 409 (in April 2022) that Perseverance took the first surface-based images of the Three Forks area. These comprised two sets of three high-resolution Navigation Camera (Navcam) stereo images of a candidate SRL landing zone, each image having 5120 x 3840 color pixels and spanning a 96° x 73° field of view. Additional high-resolution images were taken on sols 413, 414, 433, and 434 as Perseverance drove through the sample depot. These images were reviewed by MSR and M2020 teams and used to plan depot construction while Perseverance explored the Delta area over the next seven months.

The requirements for the depot changed significantly in the months leading up to its creation. NASA and ESA announced in July 2022 that the MSR architecture had changed its sample-collecting strategy from use of a newly developed ExoMars-derived Fetch Rover to use of Perseverance and two Sample Recovery Helicopters instead [1]. That led to the following constraints in designing the Sample Depot:

SRL landing zone—The entire depot needed to be within 200-700m flight distance from a location for SRL landing, close enough to enable single-sol SRH flights.

Recovery helicopter access— A 5.5m radius circle around each drop zone must be free of SRH hazards. The drop must be within 70-95cm of the center to allow it to encompass a donut shaped landing zone and a central drive, grab and go zone. SRH is expected to weigh around 2.3kg including small wheels and a gripper for which even a rock 2 cm tall could be a potential hazard.

No communication obstructions—such as the rover body or terrain could block the Perseverance High Gain Antenna since that is how Perseverance nominally receives instructions from Earth. This had to be factored in for the approach and parking heading for each drop zone.

View of the next drop zone— had to be unobstructed by the rover body to take high-resolution images for checking recovery helicopter hazards.

Rover return access—had to be maintained to allow driving through the Sample Depot after drops in case there was a need to re-image or topple any tubes that landed upright using the lower drill stabilizer tip.

4. ROBOTIC OPERATIONS

Figure 4 shows the drive path planned to meet the constraints described in Section 3.

To create the depot, Perseverance alternated between two types of sols:

Drop and image— used choreographed moves between the Perseverance external robotic arm and the Adaptive Caching Assembly (ACA) inside the rover, which has a second robotic arm - the Sample Handling Arm - to image the sample before and after dropping it on the surface. Each Mars sample is contained within a 7inch (18.6cm) tube and glove combination called the Returnable Sample Tube Assembly Glove Assembly (RGA). A subset of the drop and image sols included additional pre-drop imaging of the tubes by the WATSON (Wide Angle Topographic Sensor for Operations and eNgineering) camera on the end of the rover's robotic arm. These images were used to confirm successful operational prevention of tube cracks previously observed during ground testing. All drop and image sols concluded with post-drop WATSON images of the RGA on the surface to verify its location and support safely driving away in the next plan.

Drive and photoshoot— began by backing up to take mid-drive images of the dropped sample tube. Each drive would then conclude with a precision approach to place the ACA sealing station over the next drop zone. Drive distances between drop zones (DZ) ranged from 8m-22m, as shown in Table 2. If the post-drop WATSON images indicated the RGA settled near a wheel, an RGA Avoidance Maneuver would be executed to back away from the RGA without contacting it.

Sampling Operation Development

In accordance with prior ACA operations, significant development work was completed to limit the complexity of the activity for operators. A pre-defined drop table was established, with clear guidance on the drop order and which tubes required the additional WATSON imaging (Table 1). At the start of a given shift, sampling operators needed only to reference the table, select the hardware in the sequencing, and treat the resulting activity like any other ACA operation. Considerations about whether it would be safe to drop the tube and the likelihood of the tube ending up in an undesirable location (e.g. under a wheel) were addressed through depot site selection and an extensive drop test campaign, eliminating the need for real-time analysis.

The limited complexity for sampling operators was made possible by the repeatability of the function being performed by the ACA. This was coupled with deliberate sequencing practices that allowed the same ACA command products to be run for each of the RGAs dropped. These ACA command products were then interleaved with Arm commands to image RGAs as specified for each sol.

The five sample drops that did not include pre-drop WATSON imaging were executed by running a complete ACA drop activity, followed by a post-drop robotic arm activity to image the RGA on the ground. Pre-drop WATSON imaging required more coordination between ACA and arm motions, and this specific coordination was achieved through testing of the positioning of the sample handling arm within the ACA in relation to the external arm positioning to ensure that the top of the tube was visible in the images acquired.

In addition to the standard suite of testing required to prepare command products for execution on Mars, ACA operation development also included a dedicated drop test campaign. Through this campaign, over one hundred drops were executed on simulated Three Forks terrain, with the intent of bounding the possible offset between the intended drop target and the final resting position of a dropped RGA.

There were multiple factors observed that determined the final resting position and orientation of an RGA after it was dropped. The primary factors that were identified and characterized in testing are:

Rover tilt—RGAs were dropped from the Adaptive Caching Assembly approximately 90 cm above the ground, resulting in an offset in impact location relative to the rover when dropped with vs without up to 3 degrees of rover tilt.

RGA interaction with terrain—As RGAs dropped with gravity to the surface below the rover, there was some variability in the orientation with which they hit the ground. This, coupled with the terrain differences at each drop site, resulted in varying RGA dynamics upon impact with the terrain.

RGA interaction with drop hardware— RGAs hung with minimal constraints within the Adaptive Caching assembly immediately prior to dropping, allowing some motion of the RGAs relative to the drop hardware before falling to the surface.

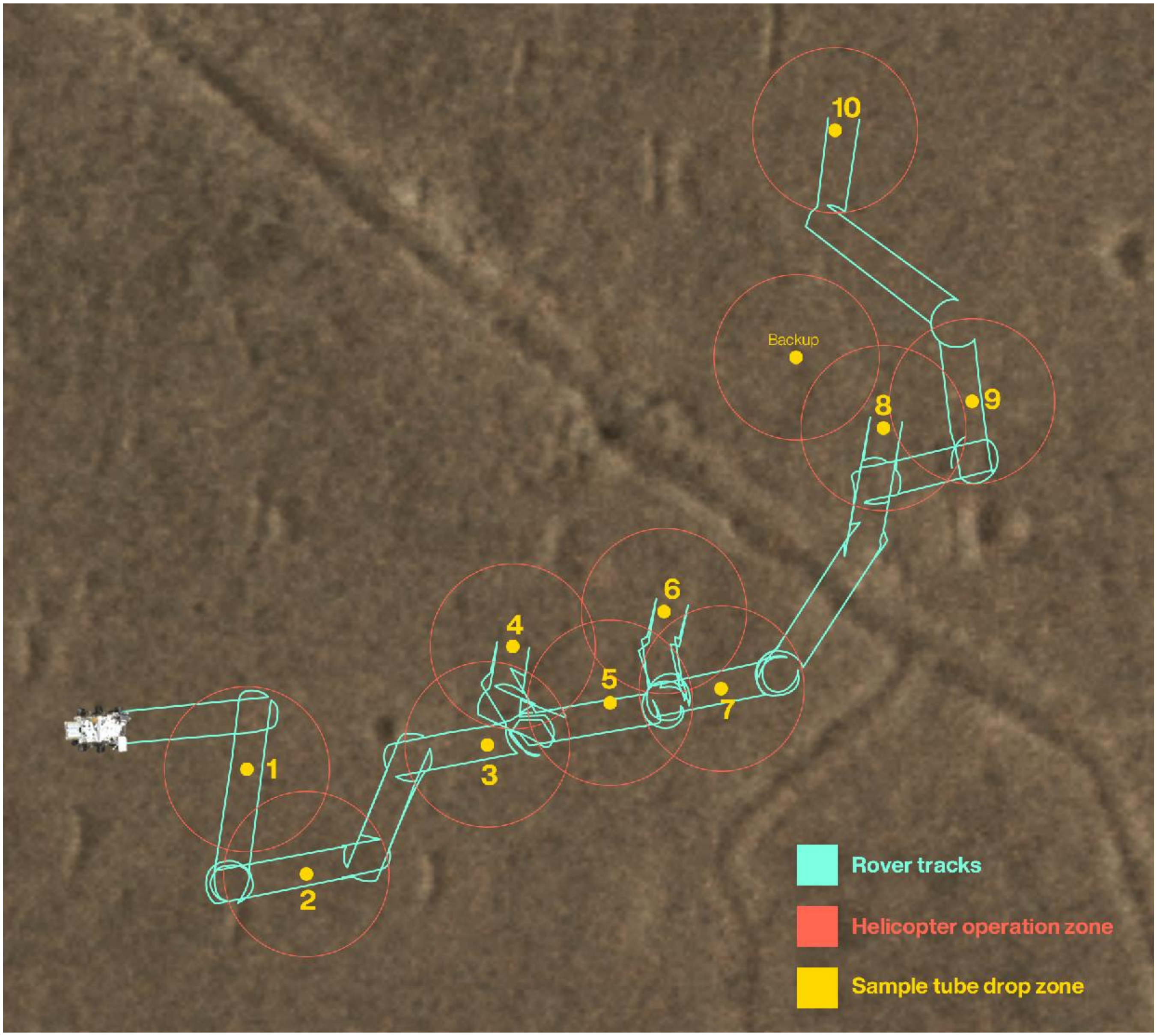

Figure 4. **The drive path planned for sample depot creation.**

Table 1. **Tube drop table with as-executed results.**

RGA ID	DZ ID	Tube ID	DZ Radius	Pre-Drop WATSON?	Sol Dropped	RGA Horizontal?
Malay	26	01	95 cm	Y	653	Y
Mageik	25	28	95 cm	Y	655	Y
Crosswind Lake	22	17	95 cm	Y	661	Y
Roubion	21	29	95 cm	N	666	Y
Coulettes	20	34	95 cm	N	668	Y
Montdenier	18	13	70 cm	Y	672	Y
Bearwallow	19	14	70 cm	Y	675	Y
Skyland	17	24	95 cm	N	680	Y
Atsah	16	36	95 cm	N	682	Y
Amalik Witness Tube	13	40	70 cm	N	690	Y

The characterization of each of these factors in Earth-based testing was necessary to provide a likelihood of RGAs coming to rest in an undesirable location, and these results were used to define the structure of the drop activities. They ensured that the recovery helicopter access constraints would be met, and that the activity was appropriately set up to prevent driving over a dropped RGA.

Mobility Operation Development

To facilitate efficient mobility planning shifts, a highly-detailed strategic plan was prepared for depot construction. While a typical strategic drive plan for Perseverance provides a general route for operators to follow, the sample depot plan specified implementation details such as distance, imaging, heading, and steering for each drive in the depot. By following this pre-approved strategic plan, operators were able to quickly satisfy the depot constraints without deliberation during tactical planning. To assist implementation of each drive, a validation tool was created to compare the operator's work against critical aspects of the strategic plan - order of activities, drive parameters, and depot targets. This tool provided real-time feedback during tactical planning, helping operators correct mistakes while they were drafting the drive.

Target Management—As with most mobility operations, target coordinates were used to transfer information between teams during depot construction. A target naming convention was developed to ensure consistent references throughout the campaign and allow automated tools to monitor and evaluate targets as they were created. A database was established to track the position of dropped RGAs across multiple sols to help operators avoid driving over them. A script was used to update the target database after each drive and automatically create new, localized targets that the operators could use during planning.

Drive Accuracy—One challenge for mobility operations during sample depot construction was parking accuracy. The rover needed to position the ACA sealing station over the RGA drop target with minimal error, or the drive would need to be repeated. Relative to the rover navigation frame origin between its middle wheels, the ACA sealing station is 0.711 m forward and 0.242 m port. Perseverance's onboard software already supported precision driving relative to arbitrary control point coordinates, but MobSketch[15], the graphical planning tool for drive activities, required an update. Additionally, a gravity vector visualization was added to HyperDrive[15] to provide the best estimate of where the RGA would land. This gravity adjusted drop point was reviewed by the M2020 and MSR planning teams as part of the process for approving each drop.

5. FAULT PROTECTION

The Three Forks sample depot construction was a critical part of both the M2020 and MSR missions and it was executed with a risk posture to reflect that. All command products used in flight were tested extensively on the ground. Contingency procedures were developed to recover from all envisioned fault scenarios. Complexity of daily operations was limited and ground in the loop confirmations were required to ensure the safety of the samples, despite the additional sols it would cost.

Visual confirmation of RGA after drop—One such activity motivated by sample safety was the post-drop WATSON images. These images provided confirmation that the RGA drop had occurred successfully and allowed operators to know exactly where the RGA ended up relative to the rover wheels. The danger of driving a wheel over the RGA as the rover backed away was enough to force an extra ground in the loop cycle and double the amount of sols it would take for depot construction, although there were many other considerations that also motivated separating the RGA drop sol from the drive sol - plan complexity, power availability, and more.

RGA Avoidance Maneuver Contingency

Due to the dynamic nature of the RGA drop, it was impossible to guarantee the RGA would not come to rest next to one of the rover wheels, although the drop test campaign showed this was statistically unlikely. Because of its low-likelihood, a recovery procedure was created but command products were not pre-developed for this scenario. The procedure was not overly complex, describing a few specialized arcs that could be used to maneuver away from the RGA without putting it at risk. This recovery could be planned in the same plan as the next depot drive, maintaining the depot construction schedule. This contingency addressed all situations where the RGA was near but not touching a wheel, including when it was not possible to steer the front wheels because of how close they were to the RGA.

Figure 5. RGA resting vertically following drop to terrain in test.

The depot construction team decided that if the RGA ended up touching a wheel after being dropped, a stand-down day was acceptable to reproduce the scenario on Earth in JPL's MarsYard and develop a custom recovery plan. This decision was driven by the extremely low likelihood of such a scenario combined with the uncharacterized dynamics of driving while a RGA was in contact with a wheel. To prevent an RGA from bouncing or rolling into a wheel (which was identified as an unrecoverable situation), the front wheels were steered so that the wheel opening would not face the RGA drop point when parked.

RGA Topple Contingency

In executing the drop test campaign to characterize post-drop RGA positioning, one of the drops resulted in an RGA resting vertically on the base of its glove assembly as shown in Figure 5. Sample recovery helicopters are being designed under the assumption that RGAs will be resting horizontally on the terrain, so a contingency operation was needed to topple any RGAs that landed in this orientation on Mars.

The contingency sol path was to be initiated if an upright RGA was discovered in the post-dropoff WATSON images. The first sol would involve a short backward drive such that the RGA was within a reachable corner of the arm workspace followed by workspace imaging. Rover Planners would then define a target at the center of the RGA using these images and uplink a pre-planned Tube Topple robotic arm sequence associated with this target, which would be executed on the second sol. Workspace images would again be taken at the

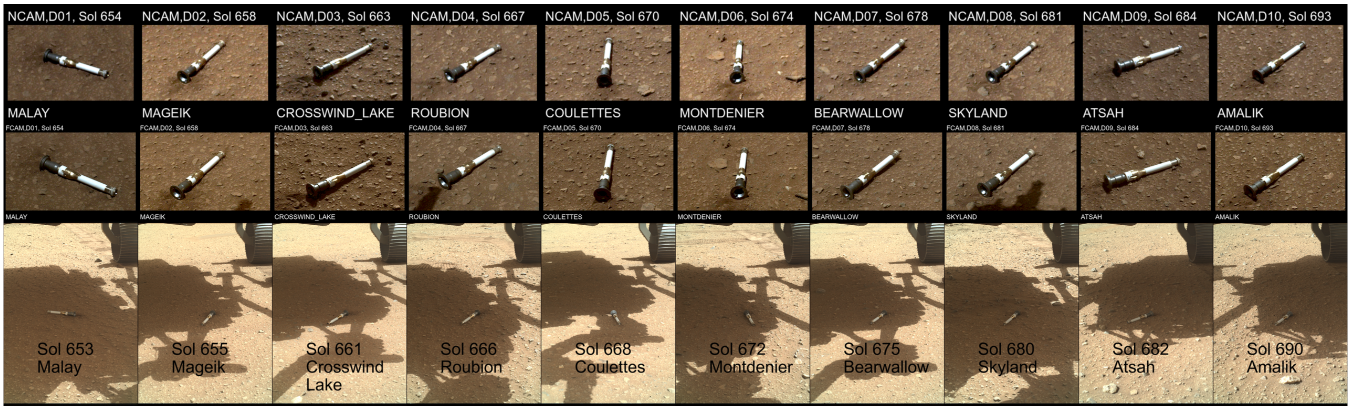

Figure 6. Documentation images of each sample tube in the Three Forks depot: Navcam (top row), Front Hazcam (middle row), and WATSON (bottom row).

end of the second sol to confirm that the tube was toppled, or to aid with a repeat of the toppling activity.

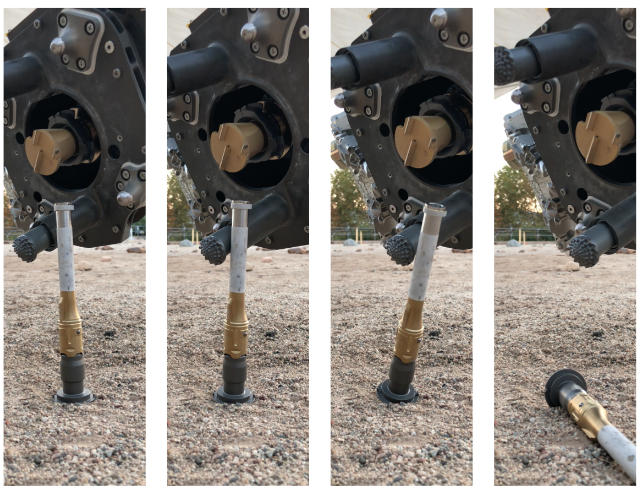

Figure 7. RGA toppled by swiping stabilizer laterally during a performance characterization test.

To minimize tactical complexity, the Tube Topple robotic arm activity was designed to be robust to uncertainties and avoid hardware damage risk and contamination. Trade studies and tests were performed in the months prior to sample depot creation, converging on an implementation akin to a serpentine scan. This involved positioning a drill stabilizer away from the tube at a shallow 25 degree angle above the ground plane at a desired ground standoff, approaching the tube in 1 cm increments over a distance of 20 cm, and swiping 30 cm laterally at each step, with the direction reversed at each step. In doing so, the tube would be toppled when the stabilizer shaft contacted the body of the tube as shown in Figure 7. The large ground patch and multiple contact attempts ensured a high rate of success and robustness to arm placement and RGA target designation uncertainties. Hardware damage risk for the RGA and arm was also minimized by limiting contact forces, thereby minimizing possible jamming scenarios.

Imaging

During depot construction, systematic documentation images of the tubes were acquired by the Navcam [17], Front Hazcam [17], and WATSON cameras [18]. Image viewing geometries for each camera were identical across all tube drops, allowing direct comparisons of tube positions and orientations relative to the rover for all tubes (Figure 6). The Navcam and Front Hazcam images were acquired as stereo pairs, enabling the determination of tube locations and orientations relative to a local Cartesian site coordinate frame within the Three Forks depot (Figure 8). To ensure a complete set of high-quality stereo data across all lighting and orientation combinations, the Navcam and Front Hazcam images were acquired using an exposure bracket technique in which three sets of full-resolution stereo pairs were acquire per tube (low exposure, nominal exposure, and high exposure) [19]. As shown in Figure 10, the positions and orientations of the tubes were relatively repeatable across all 10 tube drop activities. At the end of depot construction, a high-resolution documentation panorama was acquired by the Mastcam-Z [20] cameras (Figure 11). All of the Three Forks sample depot image data have been archived in the openly accessible NASA Planetary Data System (PDS) [21], [22] [23], [24].

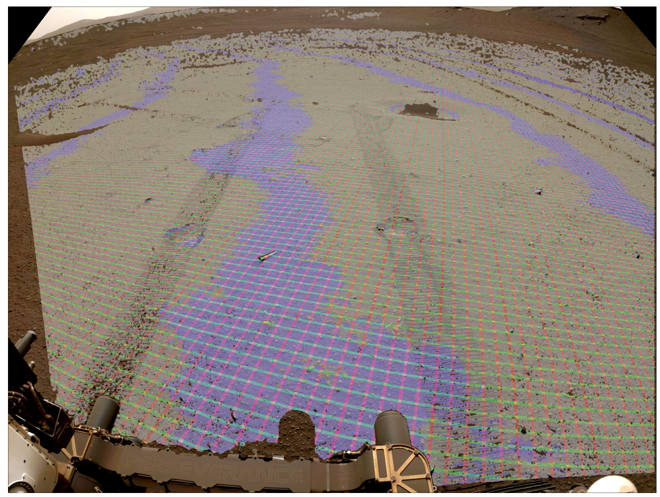

Figure 8. Navcam image from Sol 663, showing the Crosswind Lake sample tube position and orientation. The cross hatch pattern overlay shows 10-cm contours of x (red lines) and y (green lines) coordinates in a local Cartesian site frame. The purple contour represents the height (z) of the local surface. The sample tube is located near the center left of the image.

Table 2. Sol by sol breakdown of the creation of the Three Forks Sample Depot. Horizontal lines separate activities planned during a single Earth planning day. There were multiple "no planning" sols due to weekends, holidays, fault recovery, and occasionally restricted sols due to inconvenient alignment between the daytimes on Earth and Mars. The Outcome column lists drive distances in meters (distances from turns-in-place are modelled as no motion, since the rover center remains in place), and radial distance from the optimal drop off location in centimeters. Green labels indicate Success, blue labels indicate partial completions that succeeded, but did not reach the next goal state completely, and red labels indicate faults that halted progress unexpectedly.

Sol	Type	Outcome	Sample
652	Drive to Zone	Success 36.8 m , 38.4 cm	
653	Drop RGA	Success	1 **Malay**
654	Drive to Zone	Success 10.3 m , 29.1 cm	
655	Drop RGA	Success	2 **Mageik**
656	no planning (weekend)		
657	no planning (weekend)		
658	Drive to Zone	Success 18.0 m , 48.8 cm	
659	no planning (holiday)		
660	no planning (holiday)		
661	Drop RGA	Success	3 **Crosswind Lake regolith**
662	no planning (holiday)		
663	Drive to Zone	Success 8.5 m , 40.0 cm	
664	no planning (weekend)		
665	no planning (weekend)		
666	Drop RGA	Success	4 **Roubion**
667	Drive to Zone	Success 10.0 m , 9.6 cm	
668	Drop RGA	Success	5 **Coulettes**
669	no planning (weekend)		
670	Drive to Zone	Success 8.0 m , 24.2 cm	
671	no planning (weekend)		
672	Drop RGA	Arm Fault after dropoff	6 **Montdenier**
673	Close cover after Arm Fault	Success, but only partial activity	
674	Stow arm and Drive to Zone	Success 8.4 m , 14.7 cm	
675	Drop RGA	Success	7 **Bearwallow**
676	no planning (restricted)		
677	no planning (weekend)		
678	Drive to Zone	Success 22.2 m , 48.6 cm	
679	no planning (weekend)		
680	Drop RGA	Success	8 **Skyland**
681	Drive to Zone	Success 16.0 m , 19.7 cm	
682	Drop RGA	Success	9 **Atsah**
683	Science Observations (weekend)	Success	
684	Drive to Zone and Selfie	Success 20.9 m but shy of goal, 41.8 cm	
685	no planning (weekend)		
686	Reposition for dropoff	Success 0.4 m , 12.3 cm	
687	Drop RGA	Tare Fault	10 Amalik remained stowed
688	Image entire Depot and drive away	Not sent due to prior fault	
689	no planning (recovery)		
690	Drop RGA	Success	10 **Amalik**
691	no planning (weekend)		
692	no planning (weekend)		
693	Image entire Depot and drive away	Success 48.3 m	

6. RESULTS

Between sols 652 and 693 (20 December 2022 - 31 January 2023) the rover drove 207.93m, dropped 10 sample RGAs, and took 4000 images to create and document the depot as shown in Figure 11. The activity on each sol is summarized in Table 2, and the categories and number of commands sent on each sol is plotted in Figure 12.

Execution of the Sample Depot creation went very well overall. All tubes lay flat when dropped, eliminating the need to exercise the Tube Topple contingency procedure. And even though it occurred during a winter holiday period, enough experts and team members stayed available that all operations were fully staffed. There were two faults that occurred (listed in Table 2 and explained below), but the team was able to recover from each fault quickly.

Sample Caching

WATSON Tube Imaging— Special WATSON images were taken prior to the tubes' being dropped for five of the ten sample tubes, an example of which is shown in Figure 13. These WATSON images were inspected by a team for signs of tube cracking or wear. In development testing on Earth, some tubes had exhibited cracking after seal activation, but the problem was thought to be a very low likelihood event for the Mars tubes. No evidence of cracking was observed in the

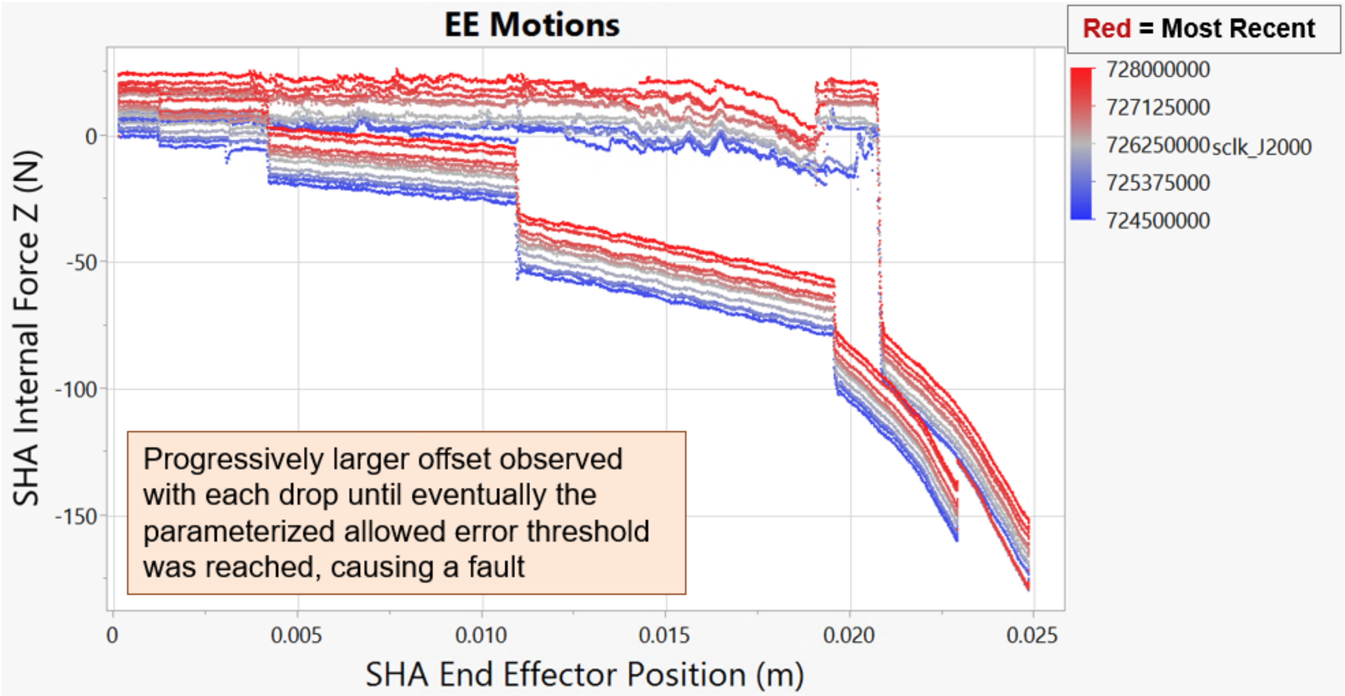

Figure 9. **A plot showing SHA internal force in the Z direction, axial along the tube length, increasing over the course of consecutive drop offs. The improper tare in each drop off sequence caused non-real forces to be book kept over time, ultimately leading to the sol 687 fault. The fault limit was set to positive 23 N while the SHA end effector was in the HOME position.**

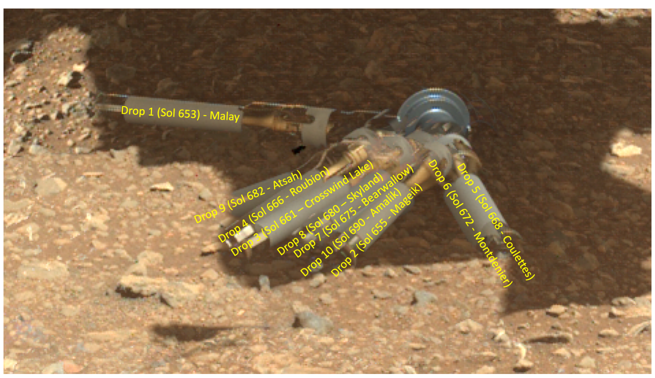

Figure 10. **Composite of WATSON images showing all 10 deployed sample tubes, demonstrating relatively consistent final positions and orientations relative to the rover.**

five flight tubes imaged.

Montdenier Arm Fault—On sol 672, the arm faulted while attempting to collect the fourth of five WATSON images of the sample tube on the terrain. A preliminary investigation revealed that this was due to a transient spike on the Shoulder Azimuth resolver at the beginning of the move, resulting in a mismatch between the angles measured from the encoder and resolver over a duration that exceeded the parameterized persistence limit. This signature was also noted to be similar to resolver transients on the Curiosity rover, which adopted a strategy of expanding the persistence upon such fault encounters. On sol 673, the WATSON cover was closed while this investigation was underway. Then on sol 674, arm recovery was successfully performed by wiggling the Azimuth joint with a wider resolver persistence to ensure steady readings before stowing the arm. No further imaging was deemed necessary and sample depot creation continued with a drive to the next drop zone. As a near-term corrective action, subsequent underbelly imaging activities temporarily widened the Azimuth resolver persistence to mitigate faults. The investigation of this issue is still ongoing to determine root cause and long-term solutions.

Amalik Witness Tube Drop Fault—On sol 687, an operation to drop off the 10th and final RGA containing the Amalik Witness sample faulted. An internal force fault protection limit was tripped while attempting to drop the tube from the sealing station. Operators reviewed the data and quickly identified a sequencing error in which forces were being incorrectly tared, leading to a build up of ”internal” forces over the course of the prior nine drops (Figure 9). Eventually, these forces increased above the positive 23 N limit while the SHA end effector was in the HOME position, triggering the fault. The sequencing error was not made evident in ground test, likely because volatile states are cleared each time the testbed is powered on, and force values are often not intentionally carried forward across test shifts.

A recovery plan was executed on sol 690, resulting in the successful drop off of the Amalik Witness Tube. Operators later corrected the sequencing error to prepare for possible future tube drops.

Mobility

The distance between RGAs was required to be at least 5.5 meters. But terrain, RGA imaging and communication considerations described in Section 3 led to the nine inter-tube drives each covering 13.6 m ($\pm\sigma = 5.4m$) of odometry on average, as shown in Table 2. These odometry estimates

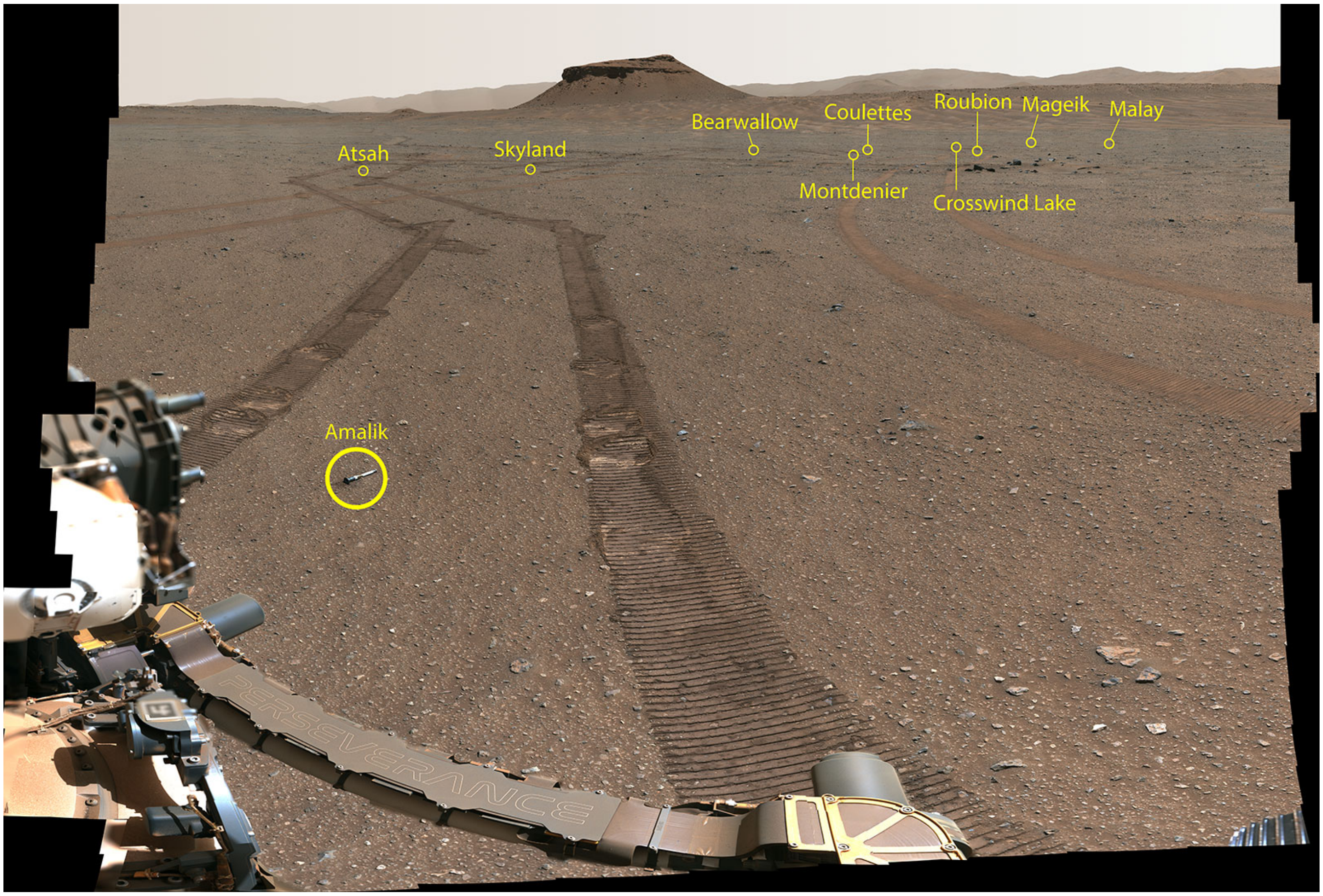

Figure 11. **Image of the sample depot, taken by Perseverance using the Mastcam-Z camera. The "Amalik" sample closest to the rover was about 10 feet (3 meters) away; the "Mageik" and "Malay" samples farthest away were approximately 197 feet (60 meters) from the rover.**

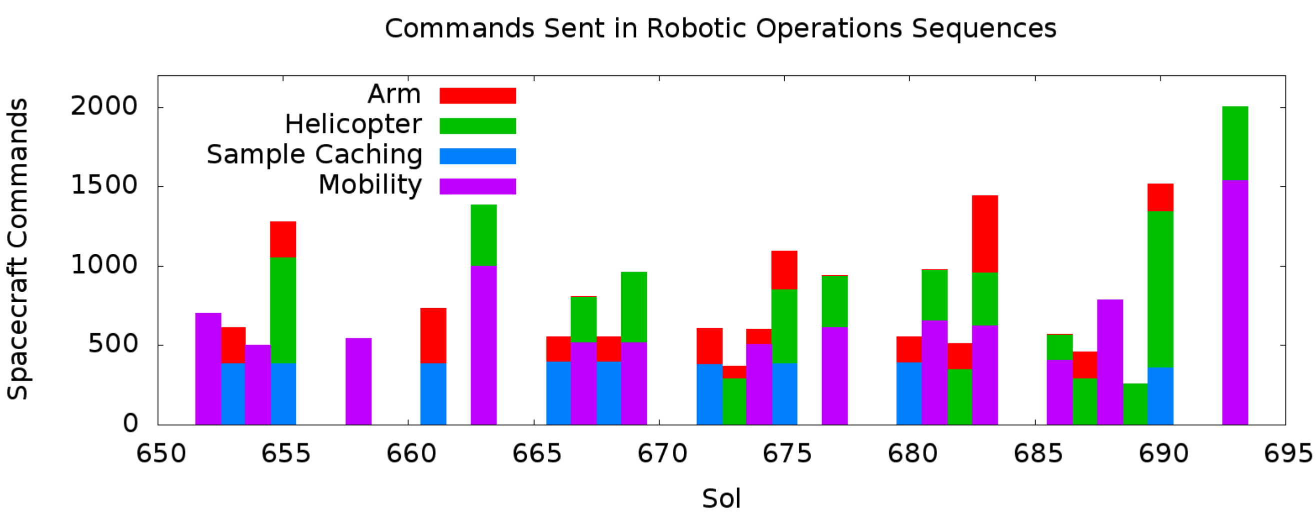

Figure 12. **Number of Arm, Sample Caching, Mobility, and Helicopter commands sent on each sol during creation of the Sample Depot cache.**

do not account for any turn-in-place motions.

A single drive was almost always sufficient to directly reach the next desired target, thanks to the onboard Visual Odometry capability correcting most of the position drift along the way [25], and ground-based localization relating the high-resolution Navcam images acquired seven months earlier to the rover's current terrain images. An MSR representative

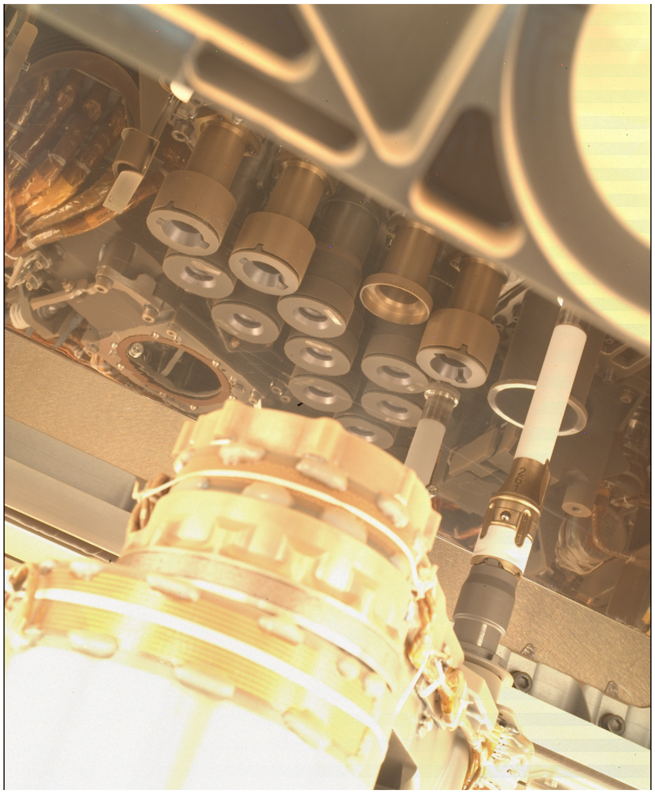

Figure 13. **WATSON tube image taken of the Malay sample tube on sol 653 at one of the two imaging positions.**

was always present during the depot construction to confirm that the each drive's final position satisfied the criteria for the next tube dropoff.

However, the drive on sol 684 did not quite reach the desired location, even with Visual Odometry enabled. Presumably the target designation error from the high resolution image localization was higher than expected. So Rover Planners had to drive an additional 0.4 m on sol 686 to satisfy the MSR dropoff constraints and ensure sufficient distance from a nearby rock several centimeters wide. That sol was the only instance of a single planned drive not achieving the desired endpoint. Sols 658 and 678 came close, each ending with the drop circle centered over 48 cm from the center of the MSR desired drop area, but in each case the terrain at the actual ending location was deemed acceptable by MSR for sample dropoff.

Final placements are summarized in the WATSON "selfie" shown in Figure 1 and the MastCam-Z mosaic in Figure 11.

7. LESSONS LEARNED

Lessons learned during the construction of the Three Forks cache include:

Understanding System-Level Uncertainty—The pose uncertainty associated with rover mobility and target selection is complicated and is a product of many sources - original target designation, stereo image processing, onboard visual odometry - to name a few. Calculating the uncertainty of positioning of the rover at each RGA drop zone was handled differently by each team, leading to analysis discrepancies. To improve this, a system-level model of the uncertainty should have been developed using input from all the teams working together, so all aspects were consistent.

Methods of Target Selection—The primary method proposed and implemented to identify the location of each RGA drop target in the local rover frame was to use a globally-referenced overlay map, localized to the rover after each drive. It was found that the original map and localization procedure introduced errors of significant magnitude compared to the accuracy required. To correct these errors, the operations team needed to include a target refinement step using our normal method of direct NavCam imaging. Had we not been able to fall back to this method, depot construction would have had significant setbacks.

Clear Procedures for Each Team—Overall, operations went very smoothly as a result of clear responsibilities and handoffs between teams on shift. Quantitative Go / No-Go criteria were defined in advance, limiting qualitative discussions that would have been difficult to resolve. The pre-defined flow of targets and information between teams worked well, minimizing discrepancies and blockages during operations. A strict target naming convention was utilized to prevent confusion and facilitate consistent documentation across all teams.

Balance between Contingency Planning, Likelihood, and Risk—It seems naive to look back and declare that preparations for low-likelihood contingencies were unnecessary because they were not needed in flight. Yet there is a cost to being over-prepared, and indeed the effort spent on low-likelihood contingencies could have been focused elsewhere to improve Perseverance operations. In hindsight, a more thorough analysis of likelihood and risk for each off-nominal scenario may have allowed us to reprioritize the team's efforts. A more direct trade between preparation in advance vs. accepting additional recovery sols could have been made for low-likelihood scenarios, which may have translated to a high probability of increased labor efficiency.

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