Enabling Long & Precise Drives for The Perseverance Mars Rover via Onboard Global Localization

Vandi Verma
Jet Propulsion Laboratory,
California Institute of Technology
4800 Oak Grove Dr.
Pasadena, CA 91109
vandi@jpl.nasa.gov

Jeremy Nash
Jet Propulsion Laboratory,
California Institute of Technology
4800 Oak Grove Dr.
Pasadena, CA 91109
jeremy.nash@jpl.nasa.gov

Lucas Saldyt
Jet Propulsion Laboratory,
California Institute of Technology
4800 Oak Grove Dr.
Pasadena, CA 91109
lucas.saldyt@jpl.nasa.gov

Quintin Dwight
Jet Propulsion Laboratory,
California Institute of Technology
4800 Oak Grove Dr.
Pasadena, CA 91109
quintin.h.dwight@jpl.nasa.gov

Haoda Wang
Columbia University
530 W 120th St.
New York, NY 10027
haoda.wang@columbia.edu

Steven Myint
Jet Propulsion Laboratory,
California Institute of Technology
4800 Oak Grove Dr.
Pasadena, CA 91109
steven.myint@jpl.nasa.gov

Jeffrey Biesiadecki
Jet Propulsion Laboratory,
California Institute of Technology
4800 Oak Grove Dr.
Pasadena, CA 91109
jeffrey.j.biesiadecki@jpl.nasa.gov

Mark Maimone
Jet Propulsion Laboratory,
California Institute of Technology
4800 Oak Grove Dr.
Pasadena, CA 91109
mark.maimone@jpl.nasa.gov

Andrei Tumbar
Jet Propulsion Laboratory,
California Institute of Technology
4800 Oak Grove Dr.
Pasadena, CA 91109
mark.maimone@jpl.nasa.gov

Adnan Ansar
Jet Propulsion Laboratory,
California Institute of Technology
4800 Oak Grove Dr.
Pasadena, CA 91109
adnan.i.ansar@jpl.nasa.gov

Gerik Kubiak
Jet Propulsion Laboratory,
California Institute of Technology
4800 Oak Grove Dr.
Pasadena, CA 91109
gerik.kubiak@jpl.nasa.gov

Robert Hogg
Jet Propulsion Laboratory,
California Institute of Technology
4800 Oak Grove Dr.
Pasadena, CA 91109
robert.hogg@jpl.nasa.gov

***Abstract*—The Perseverance Mars rover needs to drive long distances between regions of scientific interest to collect a diverse set of samples. Position knowledge is needed for navigating to the region of interest. Planetary mobile robots accumulate position uncertainty as they move. Globally localizing the robot to an orbital map of Mars removes this uncertainty. To date, this has been performed manually on the ground by humans for mobile surface and aerial robots. This can be accurate but requires communication between planets. This takes significant time and the need for it limits how far Perseverance can autonomously navigate without ground-in-the-loop.**

This paper describes a new onboard approach for performing global localization, much of which already has been successfully demonstrated on Perseverance. Our Censible technology uses a modified census transform to achieve sub-meter global localization accuracy that is robust and practical, and whose performance matches human-directed localizations from the first two and a half years of the mission to within 0.5 meters on average with no outliers. We use the fast processor on the Ingenuity Helicopter Base Station mounted in the Perseverance rover to perform the localization. It was originally installed to coordinate communication with Ingenuity. This effort developed the interfaces and radiation mitigation methods needed to enable its use as a rover co-processor. The system is designed to limit operations impact and requires no daily input from rover operators other than whether or not to perform global localization, but also allows strategic configuration options if desired. We discuss the lessons learned from developing and deploying this new technology on a flight mission, and describe how global localization is expected to increase science return and change how planetary mobile robots navigate.

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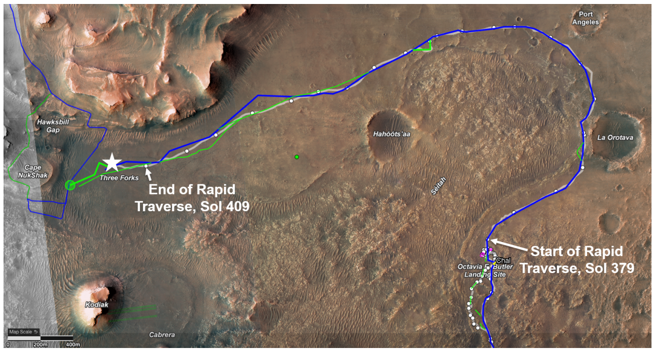

Figure 1. Illustration of the 5 kilometers of driving Perseverance completed over 31 sols during the Rapid Traverse portion of its mission (sols 379–409).

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1. INTRODUCTION

The NASA Mars 2020 mission, which includes the Perseverance rover and the Ingenuity helicopter, landed on Mars on February 18, 2021. It is part of an international Mars Sample Return campaign to collect and return Martian samples to Earth for scientific analysis. The farther it can drive between sample collection locations, the more diverse the samples can be. Figure 1 shows an example of a 5km drive Perseverance performed over 31 days to move as quickly as possible between locations of scientific interest [1]. Perseverance is currently planned to rendezvous with the Sample Retrieval Lander (SRL) to deliver its samples in the 2030s.

Perseverance is the first NASA Mars rover that can drive using its autonomous driving capabilities (Hazard Detection and Avoidance, Visual Odometry) at close to its maximum electromechanical speed. As a result, its self-driving autonomous navigation system has become its primary means of driving: it has been used to execute or evaluate 88% of the total distance traveled [2]. As of this writing, Mars solar day (sol) 925 for the mission (26 September 2023), the farthest distance it has driven without human review is 699.9m over three sols, which is a planetary rover record [2].

When planning long autonomous drives, human Rover Planners indicate safe and dangerous areas by laying out “Keep in” and “Keep out” zones on orbital maps. But as the rover drives, the uncertainty regarding its actual position on the orbital map grows. To ensure the rover remains safe, the “Keep in” (and “Keep out”) zones will shrink (or grow) onboard according to the current uncertainty. This added uncertainty can result in drives ending early if the growth in “Keep in” and “Keep out” zones blocks a narrow passage. This can only be alleviated by re-localizing the rover’s current location against the orbital map. Currently, human mapping specialists re-localize the rover before every drive plan (manually performing *global localization*). This requires a complete communications cycle, and the need for it limits how far Perseverance can autonomously navigate without ground-in-the-loop.

As a result, the maximum duration of any autonomous drive plan without human review has only been three Martian sols. After hundreds of meters, rover position uncertainty will grow to such an extent that it is impractical to navigate typical Martian terrain without using global localization to eliminate the accumulated uncertainty. This process is currently performed manually on Earth: rover operators downlink panorama images from the end of the drive and match them to an orbital map. Autonomous onboard global localization will no longer require frequent communication with Earth, removing the limitation on drive distance due to uncertainty growth.

This paper addresses the challenge of autonomous onboard global localization and describes:

- *A system for global localization for a flight robotic mission that has been demonstrated to produce results that match human accuracy on Mars data.*
- *The first demonstration using the non-radiation-hardened Ingenuity Helicopter Base Station as a rover co-processor.*

Beyond Perseverance, the absolute position estimation provided by global localization is a key enabler for future planetary robotic missions. Lunar rover missions like Endurance [3] aim to traverse many kilometers across the Moon largely in Permanently Shadowed Regions with limited communication. The Ingenuity and Sample Retrieval Helicopters also require absolute position estimation to navigate autonomously and retrieve sample tubes. The proposed system contributes a critical capability in the broader context of increasing demands for long-range autonomy in planetary robot navigation [4]. The decision to implement the MSR mission will not be finalized until NASA’s completion of the National Environmental Policy Act (NEPA) process. MSR references in this document are being made available for information purposes only.

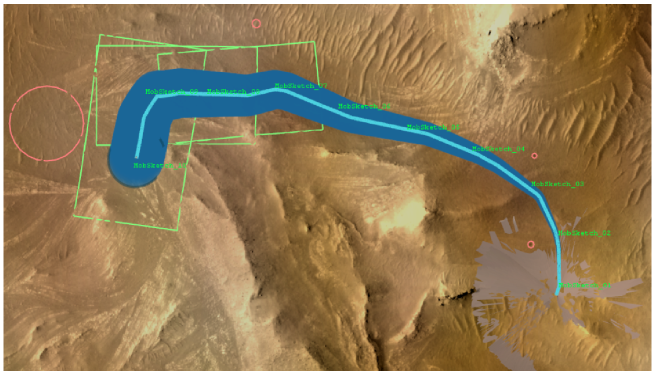

Figure 2. Demonstration of the onboard position uncertainty growth that occurs on long drives. A single set of drive instructions was sent to Perseverance on Mars to drive over multiple Martian days, sols 717-719. It drove 655.8 meters on Mars over that period, shown by the light blue line from the bottom right corner to the top left. The uncertainty, shown in dark blue, grew monotonically from 0 meters at the start of the drive to 32.92 meters at the end of the drive, because no global localization was performed during the three driving sols.

2. GLOBAL LOCALIZATION PROBLEM

Planetary mobile robots such as Perseverance and Ingenuity accumulate position uncertainty as they move. This is due to several factors including sensing and actuation accuracy, and accuracy of position estimation.

The growth of uncertainty over a long drive is illustrated in Figure 2. At the end of each drive on Mars, human mapping specialists re-localize the rover relative to the orbital map. So every new drive starts by setting uncertainty to zero at the starting location. Uncertainty then grows monotonically throughout the drive. Ingenuity is manually localized on the ground as well after each flight. Position error for Ingenuity is terrain dependant and has has been up to 13% of flight distance in complex terrain.

Perseverance autonomous navigation is successfully driving long distances making global localization a higher priority

Global localization has been a known problem for planetary robots for some time. Global localization has been performed manually at the end of each drive by human experts since the Mars Exploration Rover mission began in 2004, and the practice has continued for Curiosity and Perseverance. Prior rovers’ autonomous navigation (AutoNav) systems drove more slowly, typically only covering tens of meters per sol [2], so there had been no urgency to address this issue earlier. In contrast, the Perseverance self-driving AutoNav system has already been used to evaluate 88% of the 17.7km distance traveled during its first Mars year of operation [2]. Previously, the maximum total autonomous distance evaluated was 2.4 kilometers by the Opportunity rover during its 14-year lifetime. As a result of this improved AutoNav driving capability, the need for Global Localization is now one of the main limiting factors constraining long-range autonomous driving for Perseverance.

Perseverance is configured to assume uncertainty growth at 5% or more of distance traveled

Perseverance uses a capability called Visual Odometry (VO) to confirm and update its position estimates onboard [5]. In principle, this capability has the potential to limit uncertainty growth to 2% per 100 meters of travel [6]. However, to accommodate the potential for greater uncertainty growth (e.g., due to potential errors in attitude estimates impacting position over time) Perseverance has been configured to assume as much as 5% of uncertainty growth over distance traveled whenever VO successfully measures actual motion. Should VO ever fail to converge to a solution, that motion will instead contribute 50% of the distance traveled toward the total global uncertainty. The current value of global uncertainty thus has been a weighted sum of distance traveled with and without VO knowledge.

"Keep out" zones grow by the uncertainty

Human Rover Planners indicate safe and dangerous areas by laying out "Keep in" and "Keep out" zones; for long autonomous drives, these are all placed on orbital maps. On past missions, Rover Planners have had to estimate the rover position uncertainty at each "Keep out" Zone in the drive, and manually grow each "Keep out" Zone by the anticipated worst-case uncertainty. But the Perseverance flight software now incorporates an onboard uncertainty model directly, a capability new to Mars 2020 [7]. Uncertainty is modeled as a disc, and it grows with the odometry accumulated by the rover since the last place that human Rover Planners evaluated the nearby terrain (at which point it is reset to zero). "Keep out" Zones can be laid out based on nearby NavCam or far-ranging orbital imagery and their accuracy depends on how well localized those maps are to the current position. To account for the ever-increasing uncertainty as Perseverance drives, "Keep out" zones are automatically grown onboard by the current onboard uncertainty amount. That helps ensure that any hazards identified by Rover Planners will never be encountered by the vehicle, even if they were specified hundreds of meters away from where the rover started. This keeps the rover safe but poses challenges when using AutoNav to thread a needle between hazards.

Rover path can be blocked due to uncertainty growth

An example of how uncertainty growth can block the rover's path is shown in Figures 3 and 4.

Rover drives are pre-emptively shortened

Rover strategic route planners and tactical operators perform simulations of all drives before sending commands to Mars. If the simulated drives show uncertainty growth is likely to block a passage on Mars, the operator could choose to cut the drive short and allow the science team to recover the remaining drive time for remote science observations instead.

The characteristics of the Perseverance application, which are common to many planetary rover applications, allow us to define the problem as one of determining the global location of the rover within an uncertainty envelope on a prior map

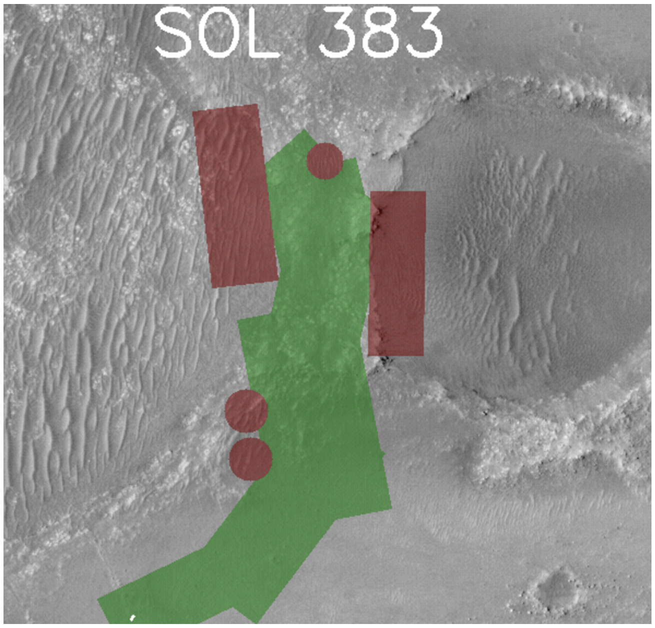

Figure 3. On sol 383 Perseverance began a 3-sol AutoNav drive to the north, with red "Keep out" zones around very sandy areas. The rover is a white dot in the lower left of the image. Green "Keep in" zones specify areas where AutoNav is allowed to consider new paths; leaving a green area and entering a red (or greyscale) region will result in a mobility fault and terminate the drive.

Figure 4. On sol 385 Perseverance AutoNav was blocked by the uncertainty-expanded "Keep out" Zones and only drove 14 meters before faulting out since there was no viable path forward. The radius of the blue circle indicates the 26.91-meter growth in uncertainty since the start of the drive, which was shown in Figure 3. "Keep out" zones have grown by that uncertainty amount, and "Keep in" zones have shrunk by the same amount. Once global localization is fully deployed, this situation will no longer occur, enabling safe multi-sol autonomous drives

using attitude knowledge and images taken with a rover-mounted stereo camera pair. But our localization approach is also adaptable to other applications that may not have the same characteristics.

3. RELATED WORK

Human-based global localization is the current practice for planetary rover missions. The Mars rovers Opportunity, Curiosity, and Perseverance have been localized by matching orthorectified navcam images to an orbital map [8], [9]. The expected accuracy is 50cm, two pixels in the 25cm resolution HiRISE map.

There has been significant interest in automating global localization on Mars. Previous approaches produce accurate localizations in many cases, but also have a significant outlier rate. This outlier rate has been a barrier to their transition into a reliable onboard capability. The low outlier rate of our approach, evaluated on a significant number of real rover images and environmental conditions, distinguishes our approach from the others.

For the Spirit and Opportunity rovers, past studies focused on matching features across the rover images, and in some cases to an orbital map, in an incremental bundle adjustment approach [10]–[23]. These approaches require terrain with unique features and struggle in terrains with few features. When matching across images without an orbital map in a bundle adjustment approach, the position error growth is more constrained than visual odometry but fundamentally still unbounded the longer the rover drives. Mission studies like Mars Science Helicopter and others have also explored a feature matching approach [24], [25].

For the Curiosity Rover, the self-reliant rover project explored a mutual information matching approach for appearance and sum-of-squared differences for elevation to match MSL navcam orthomosaics to a HiRISE orbital map [26]. Another study used an ICP-based approach to match MSL navcam panoramas to the HiRISE orbital DEM [27]. These approaches produce accurate localizations in most cases but also have a significant outlier rate.

Mars sample retrieval has been the focus of a few global localization studies. For the ESA Sample Fetch Rover, Airbus developed a global localization approach using NCC on the gradients of the DEM and appearance maps [28]: the performance on real MSL images is in-family with other NCC-based approaches. Another study focused on rover localization within a tube depot by matching rover images to a high resolution map constructed by a previous rover [29].

Lunar rover global localization has received recent attention with the upcoming Endurance rover mission and current Yutu and Yutu-2 lunar rovers. Proposed approaches use crater features for localization in the lunar daytime [30] and nighttime [31]. Craters are a more common feature in lunar terrain than in the Martian terrain traversed by Perseverance. Other global localization approaches on the Yutu and Yutu-2 lunar rover data have used feature matching and bundle adjustment across images [32]–[34].

Horizon matching is a significant category of approaches that has been applied to Mars global localization. These approaches match the horizon in the rover images to an orbital DEM, either by matching the full horizon line or features like mountain peaks. Position accuracy is typically on the order of 100m, at best 10m, depending on the nearby terrain relief [35]–[43]. These methods are also valuable for attitude estimation, although rovers like Perseverance already have a reliable capability for attitude estimation based on sun position.

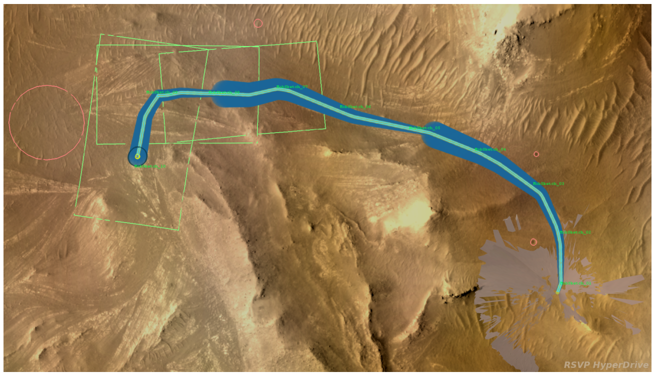

Figure 5. Results of simulating the impact of new Global Localization software on the 3-sol drive plan shown in Figure 2. Global Localization is applied onboard, once at the end of each sol's drive, and results in much smaller onboard position uncertainty overall for the drive.

Deep learning approaches to global localization are a recent trend that train a deep network to match rover images to orbital images [44]–[46]. Current approaches typically require a significant amount of training data, relying on simulation for training and evaluation. Large networks may also present a practical challenge to run on limited rover computers.

4. ONBOARD GLOBAL LOCALIZATION RESULTS

Our onboard global localization approach addresses the Perseverance problem described in Section 2. After completing a segment of driving, it performs global localization to locate the rover more accurately in a orbital map. In its simplest strategy, it performs onboard global localization once after each sol of driving in a multiple sol drive. Figure 5 shows the result from simulating the sol 717-719 drive shown in Figure 2 using the developed global localization solution, where global localization is run once after each sol (717, 718, and 719) of driving. It results in a much smaller uncertainty overall for the drive.

Accuracy of global localization

Our approach matches post-drive rover navigation camera (NavCam) panorama images to orbital maps using a modified census transform. It achieves sub-meter accuracy in global localization performance on a real dataset for all the drives for which data was available [47]. Ground-based localization has been performed for Perseverance, manually on the ground by human localization experts, since the beginning of the mission. Figure 9 shows all the rover locations in the benchmark data set where panoramas were captured and manually localized by the ground. It consists of 264 panoramas. Figures 6 and Figure 7 show the results of our global localization approach compared to the human localization for the benchmark dataset.

Our approach achieves 0.36m accuracy across 264 panora-

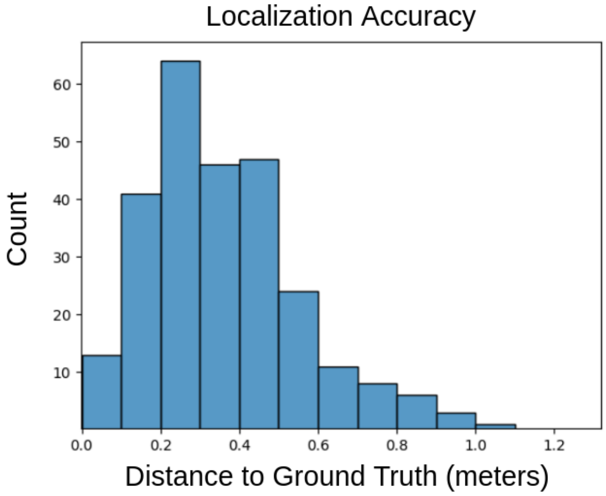

Figure 6. Localization accuracy of our approach on the benchmark data set. The x-axis represents distance from ground truth, and the y-axis is the number of post-drive panoramas out of a total 264 panoramas. The method achieves near-human performance with no significant outliers.

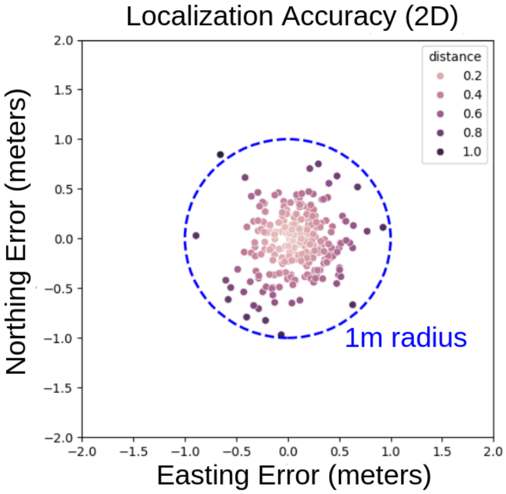

Figure 7. Localization accuracy on the benchmark data set in orbital frame (northing, easting), relative to ground truth. In nearly all cases, the error is within 1m of ground truth.

mas with no significant outliers and 99% of results coming within 0.93m of ground truth. The mode is around one-pixel error in the orbital map (0.25m). We assume a 30m search radius, which is based the max expected uncertainty after a long single-sol drive, though a larger search radius up to 100m does not significantly impact accuracy. Other common approaches, including masked normalized cross-correlation (NCC) and mutual information, produce some accurate localizations but suffer from significant outlier rates, especially with large search ranges. These alternate approaches appear to be more sensitive to outliers and lighting differences between the stereo wedges and the orbital map. This sensitivity results in more local minima and ambiguity in the correlation scores, which is not present with our modified census transform and Hamming distance approach. Figure 8 includes representative terrains showing that our approach consistently produces sharper and less ambiguous correlation peaks, and therefore more robust rover localizations, even in feature-poor and repetitive environments compared to the other methods in the figure.

Robustness to terrain variability

The rover panoramas in the benchmark dataset include the full variety of terrain that Perseverance has traversed over the 2.5-year mission. This includes images with primarily rocky terrain, sandy terrain, terrain with rover tracks, rover body or terrain occlusions, and different lighting conditions and seasons. Figure 9 includes some example panoramas. The mast-mounted NavCams have a 96° horizontal by 73° vertical field of view. When a full 360 panorama is taken on Perseverance, this typically consists of five wedges of navigation camera left and right image stereo pairs. Although sometimes operational constraints meant that only three or four stereo pairs were collected.

Robustness to variation in sun angles from orbital

Orbital images of the Jezero crater region were generally acquired mid-afternoon Mars time, which matches the times when the rover is likely to collect post-drive images. This tends to minimize differences in terrain appearance due to shadows. But some of the existing panoramas were taken mid-drive during the late morning, and our benchmark data includes panoramas from all Mars seasons over 2.5 years.

Timing results

Our approach has been run on the flight identical testbed in the JPL Mars Yard, the Vehicle System TestBed (VSTB) which includes the HBS co-processor. Testing has also been performed on the HBS on the Perseverance rover on Mars, in the phases described in section 7. Phase 2 ran global localization in only 32s, and only reached a temperature of 45 Celsius. A majority of the time for running global localization is spent in transferring images and data from the primary RAD750, known as the Rover Compute Element (RCE), to the HBS over a slow 10KB/s serial link. However, much of this can be run in parallel with other ongoing rover activities. So although the transfer takes 30 minutes, the entire activity can be safely run in parallel with other operations.

5. ONBOARD GLOBAL LOCALIZATION METHOD

Figure 10 illustrates the approach we developed for performing global localization onboard Perseverance. Similar to human-based approaches, we assume a high resolution orbital map, a set of post-drive stereo images, an odometry-based position estimate, and an accurate absolute orientation estimate as inputs. As a simplification, we assume that the rover images are captured at a similar time-of-day as the orbital map to minimize lighting differences, although our testing has indicated robustness to a wider distribution of lighting differences. The post-drive images are typically captured in the afternoon, so this assumption does not add an unnecessary constraint for our deployment.

Position uncertainty growth has typically been a problem for long drives (greater than 500m). Since the duration available for driving is limited, these drives occur over multiple sols on Mars. Therefore to simplify operations onboard localization runs once per sol at the end of the drive, in conjunction with the SunFind activity which reduces orientation uncertainty.

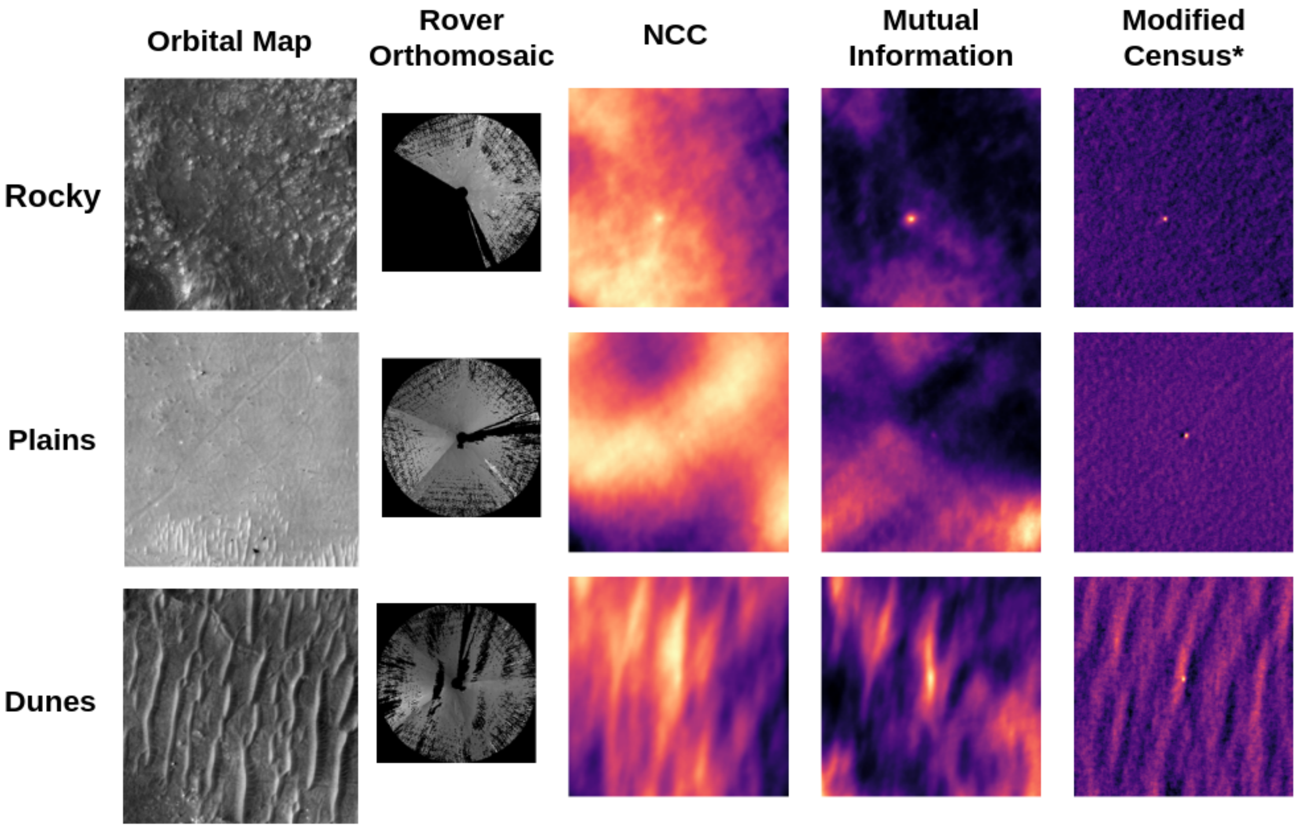

Figure 8. Comparison of correlator performance in common terrain types (rocky, plains, and dunes). The color matrices show the correlation scores for the rover orthomosaic at various locations in the orbital map: bright colors represent a high correlation, indicating the most likely rover location. Our modified census approach consistently produces sharper and less ambiguous correlation peaks, and therefore more robust rover localizations, even in feature-poor and repetitive environments.

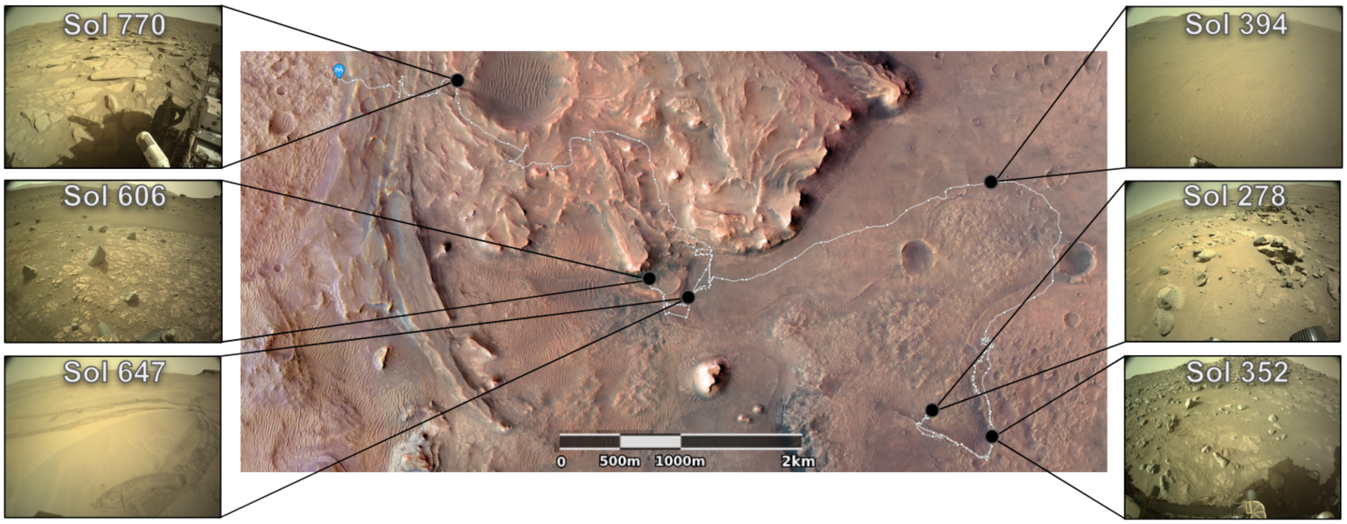

Figure 9. Locations of the 264 image panoramas covering the first 2.5 years of the mission, localized on an orbital map of Jezero crater on Mars. White dots indicate end-of-drive panorama locations, lighter white lines indicate the path the rover took between those locations. The panorama dataset includes a variety of terrain types including dunes, plains, and rocky terrain.

Global localization via census transform registration

We model rover localization as an image registration problem between the rover images and the orbital map. We take a model-based approach to make the rover images match the orbital map as closely as possible, then find a similarity measure that is invariant to the differences. With the SunFind activity running before global localization, the registration problem can be simplified to a search over 2D translation.

Similar to current human-based approaches, we first produce a top-down rover stereo orthomosaic. The rover acquires a

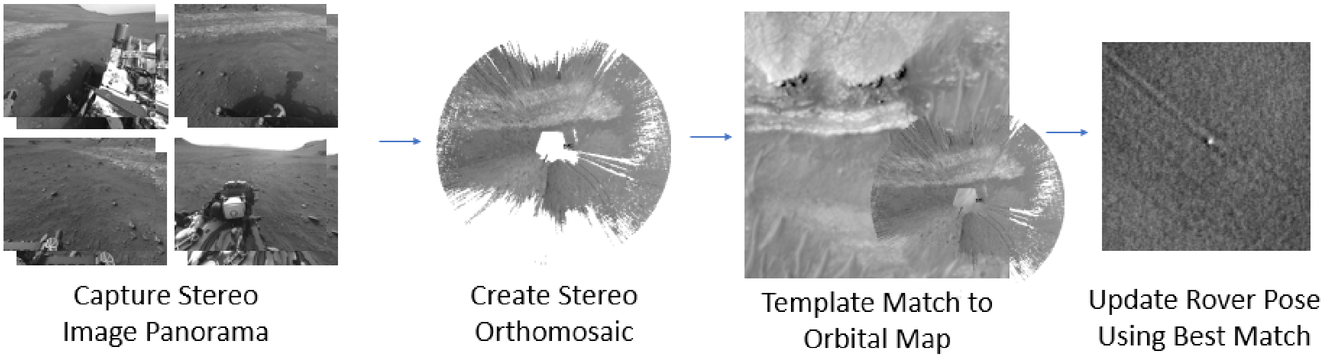

Figure 10. High-level overview of the localization algorithm.

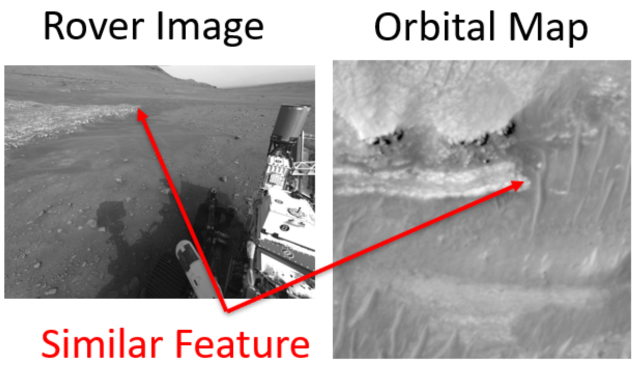

Figure 11. An example of the same feature imaged from the rover and orbital map perspectives. The matching algorithm needs to account for significant differences in perspective, appearance, and occlusions between the rover and map.

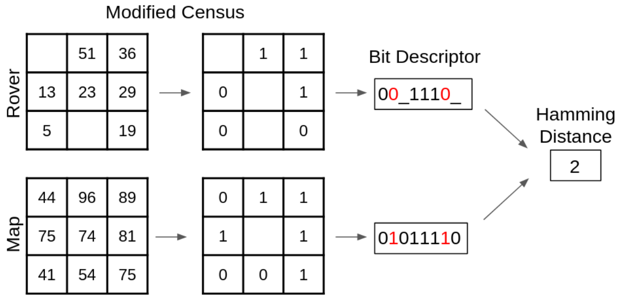

Figure 12. The modified census transform and hamming distance depicted on corresponding pixels in the rover orthomosaic and orbital map. The transform compares the center pixel value to its 3x3 pixel neighborhood to form a bit descriptor for each pixel. The descriptors are compared by counting the number of different bits (shown in red). If the rover orthomosaic is missing pixel data due to occlusions, those bits are not included in the Hamming distance.

360 panorama of NavCam stereo pairs around the rover, typically five overlapping pairs. The images are radiometrically corrected to remove vignetting and exposure time differences, and each pair is stereo-matched using semi-global block matching to produce a point cloud. The point clouds are projected into a 2D grid that matches the resolution of the appearance map (25cm) and DEM (1m).

The rover stereo orthomosaics are then matched to the orbital map using a template-matching approach. The similarity measure for the appearance map is a modified census transform and hamming distance and sum-of-squared differences (SSD) for the DEM. The modified census transform produces an 8-field descriptor for each pixel location in the rover stereo orthomosaic and map, encoding whether the pixel has a larger intensity than its neighbors, or if the neighboring pixel is missing data (Figure 12). Missing data in the rover orthomosaics is common due to occlusions from rocks and the rover body, and the modified transform and hamming distance do not penalize missing data. The census transform is also invariant to monotonic variations in intensity (morphological invariance), a useful property for matching between a rover camera and orbital camera with different camera response functions and different dust optical depths that affect contrast.

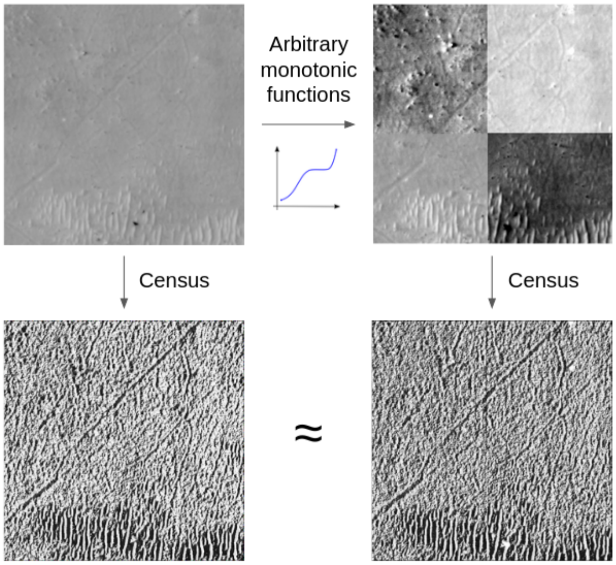

Figure 13. Applying arbitrary monotonic functions to sections of an image results in the same census transform (with the exception of the section borders) while preserving dense local information about relative intensities. This is a useful property when matching an orbital image to a rover orthomosaic that has different lighting between stereo wedges and different camera response functions.

The correlation scores from the appearance map and DEM are summed together, and the minimum score is converted into a delta position update. Greater weight is placed on the appearance map scores. Accuracy is fundamentally limited by the map resolution, so a subpixel location is estimated by

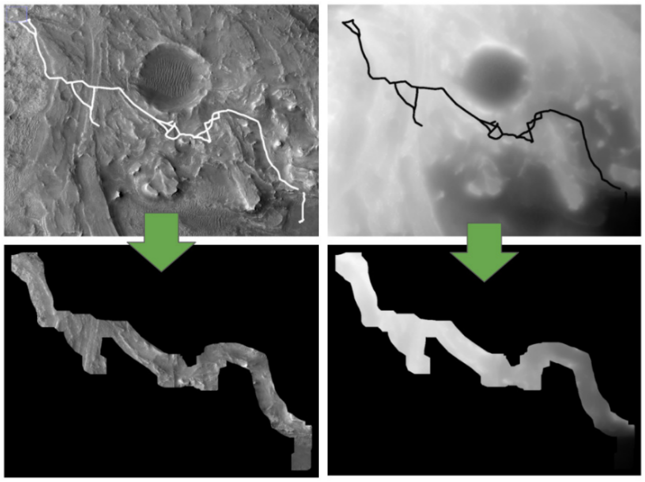

Figure 14. An example orbital appearance map (left) and DEM (right). To reduce map file size, any areas outside of a 100m radius of the strategic route are masked out.

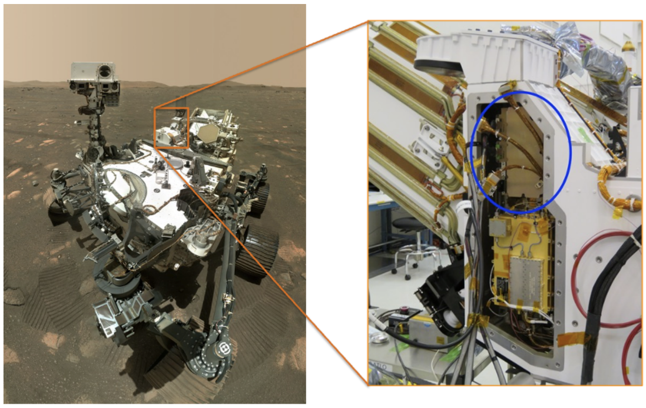

Figure 15. Location of the Helicopter Base Station on the Perseverance Rover. Its Snapdragon 801 processor is connected to the Rover's RAD750 by a serial cable, with its maximum bandwidth currently set to 10KB/s.

fitting a 2D quadratic to the 3x3 pixel neighborhood of scores around the best score. To convert between the map frame and the rover frame, a small-scale correction is applied along the easting axis based on the rover's current latitude and the equidistant cylindrical map's latitude of true scale.

The orbital map is a digital terrain model (DTM) and orthomosaic of HiRISE images produced by the USGS. HiRISE is the highest resolution pushbroom camera orbiting Mars with around 25cm resolution, mounted on the Mars Reconnaissance Orbiter (MRO). MRO is currently in a sun-synchronous orbit that captures images in the mid-afternoon in Mars local time. The images are captured with the HiRISE RED channel, which is sensitive to red and near-infrared (NIR): likewise, the rover images are processed as monochrome red images, which is spectrally the most similar to the red/NIR map. The map projection chosen is an equidistant cylindrical projection with a latitude of true scale of 18.4663 (known as the Jezero Crater Projection) for consistency with the current human localization process.

Reducing the file size of the system was a driving factor in design. Due to the limited bandwidth between Earth and Mars, the total size is limited to a few megabytes. The largest contributors to file size are the maps and the flat field images for radiometric correction, both originally on the order of tens of megabytes. The flat field images are replaced with a radial polynomial model that reduces the size to a few kilobytes. The map file size is reduced through multiple steps: 1) any parts of the map that are not within a 100m radius of the upcoming strategic route are masked out of the image, 2) the DEM elevations are discretized to 1cm resolution and converted to a 16-bit image, 3) the appearance map resolution is optionally reduced, for example to 50cm resolution, and 4) both maps are compressed using JPEG-XL lossless compression, which is typically half the size of PNG lossless compression. The total file size is on the order of a few megabytes.

6. NOVEL ROVER CO-PROCESSING

Perseverance's main computer is fundamentally specialized for reliability through hardware-based radiation mitigation. The difficulty, cost, and engineering compromises of developing and testing radiation-certified computers result in the computational capability of the RAD750 lagging decades behind modern computers. Perseverance includes a "Vision Compute Element" (VCE) co-processor which contains a second RAD750 with an FPGA specialized for stereo and visual odometry. This enables "Thinking While Driving" mobility, in which nearly all autonomous computation is completed before the drive wheels finish each commanded motion. This has resulted in record-setting distances compared to other rovers, e.g., 700 meters over three sols without human review [2]. However, its VCE FPGA resources are consumed to support a fast stereo and VO implementation for this capability. Fortunately, Perseverance also has a Snapdragon 801 computer, courtesy of the *daring and mighty* Ingenuity mission.

The Mars Helicopter, Ingenuity, is a technology demonstration to test powered, controlled flight on another world for the first time [48]. Ingenuity is a lightweight 1.8kg solar-powered helicopter, but was not designed to communicate directly with Earth or Mars orbiters. Instead, Perseverance relays data to and from Ingenuity via a Snapdragon 801 processor and radio mounted on the rover's Heli Base Station (HBS), shown in figure 15.

When helicopter flights are not being performed, the Helicopter Base Station is available as a powerful co-processor for Perseverance. The performance vs. reliability tradeoffs between the RAD750 and Snapdragon 801 computers encourage a co-processing regime, where the RAD750 handles critical real-time processing, and the Snapdragon runs computationally intensive programs. Global localization is an ideal first application of rover co-processing, as localization both has a high impact on the mission and is relatively easy to implement in a co-processing regime since it can be run offline and its results can be verified independently.

Compared to the rover processor, the helicopter base processor is significantly faster and has more memory. A comparison is shown in Table 1. While the localization algorithm runs in $\sim$32 seconds on Snapdragon, it would take an order of magnitude longer on the RAD750. Also, the algorithm had the option to use 0.5GB of memory, which is more than the

Feature	Perseverance RAD750	HBS Snapdragon 801
CPU Frequency	133 MHz (x2)	4 cores, 2.36 GHz
Memory	128 MiB ECC RAM	1.55 GiB non-ECC RAM
Storage	2GB validated ECC	32GB unvalidated ECC
Operating System	VxWorks 6.7	Linux 3.8
Architecture	PowerPC	ARM
Hardware Accelerators	FPGA (VCE)	GPU, DSP
Radiation Hardened	Yes	No
SEEs/bit/second (sim)	7.80716e−14	2.49620e−10
SEEs/day/device (sim)	13 (corrected)	4313 (uncorrected)

Table 1. Comparing Perseverance's main RAD750 computer to the Heli Base Station co-processor

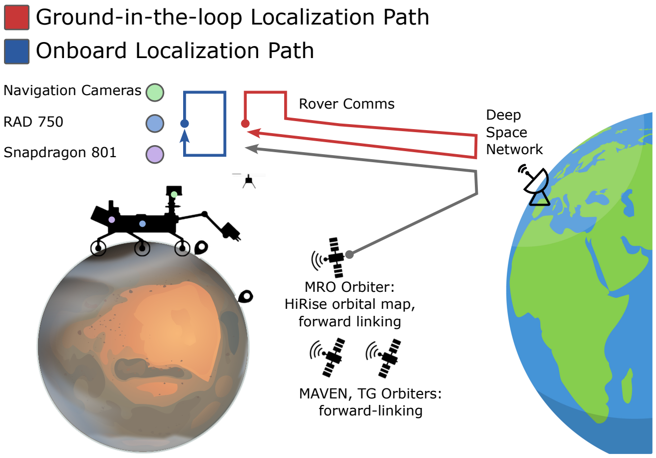

Figure 16. Localizing the rover has historically relied on a costly ground-in-the-loop. Using the Snapdragon 801 as a co-processor enables localization entirely onboard the Rover.

RAD750 has available. The HBS co-processor therefore provides a fundamental increase in compute capacity, enabling Perseverance to run modern algorithms for global localization and other applications in the future.

Co-processing reduces risk, since errors that occur on the co-processor can be isolated from the rover's primary systems. The Linux operating system on the Snapdragon 801 is much more flexible and modern than VxWorks, even if it is not specialized for real-time applications. Errors that would be considered "fatal" if they occurred on the RCE can often be recovered from on Linux. And the RCE can choose to ignore results from the co-processor if certain sanity checks do not pass. Section 7 describes the software isolation we implemented to reduce risk when performing localization with our co-processor.

Co-processing improves operational efficiency since updates and verification of the co-processing software can be made independently of rover flight software. For context, significant updates to the Rover's main software typically only happen at most once per year, and proposed changes go through a formal approval process that is often extremely conservative, given the risk of mistakes. In contrast, updating software on the HBS requires only team-level approval and scheduling a file upload via satellite. In combination with simulation, testing, and efficient review, software updates can safely occur monthly. The remaining bottleneck is satellite uplink bandwidth. Small patches or scripts can be uploaded daily.

Challenges in using the HBS as a co-processor stemmed from the original design, which was purely intended for communication with the helicopter. The serial link between the RCE and the HBS is fixed at 10KB/s, a rate originally intended to reduce impact to the RCE's processing. This limits the speed at which files may be transferred between the two computers, which often dominates processing time by 75%. However, bandwidths of up to 40KB/s could become possible with an RCE flight software update. The order-of-magnitude difference in RCE and HBS speeds made it difficult to synchronize communications between the two computers.

The BAE RAD750 spec sheet shows an expected 0.02 bits corrupted per day given a radiation environment at 90% of worst-case GEO. In contrast, a CREME-MC simulation for the Snapdragon 801 using data from a previous study [49] shows roughly 4314.3 bits expected to be corrupted per day under similar conditions. Thus, despite the increased speed of the Snapdragon 801, ensuring that results from this COTS computer are correct in the presence of radiation is a challenge. We address this in Section 7.

7. FLIGHT DEPLOYMENT

Because Perseverance is a science-critical multi-billion dollar mission, the main constraint is *risk*. New capabilities, however beneficial, need to be carefully proven to be safe. To achieve deployment to flight, our global localization project was broken into three distinct phases: software sandboxing demonstration, modular flight demonstration, and closed-loop flight demonstration.

Phase 1: Software Sandboxing isolates the global localization algorithm from the rest of the rover's flight software. In general, sandboxing and isolation allow running more experimental algorithms with less risk to the flight system. Potentially mission-ending software failures like segmentation faults or memory leaks become relatively benign if they occur within a sandbox. These types of errors can be isolated and reported by the HBS flight software. The first flight phase of this mission focused on demonstrating the safety of the software sandbox.

The Heli Base Station runs Linaro Linux, which in general is a much more forgiving and flexible software environment than VxWorks. In 2023, there are many strong options for software sandboxing, such as Docker or LXC, but this project uses the absolute simplest approach, which applies the built-in "change root" Linux system call for filesystem isolation, and the "ulimits," "chrt," and "taskset" programs for basic resource isolation. While simple, this approach was chosen because it avoids forward-linking additional software to the rover or interfering with Ingenuity operations. Despite its simplicity, it is sufficient to mitigate common potential errors and was intentionally tested against fake malicious code such as memory leaks, segmentation faults, thread bombs, and filesystem erasure. Even though the software sandbox can contain errors like these, the global localization algorithm was reviewed and tested to a high standard since it is the first demonstration of this capability.

This phase ran successfully on sol 859 (21 July 2023).

Phase 2: Modular Flight Demonstration Once the prototype localization algorithm was completed and tested extensively on Earth, it was uploaded to the spacecraft and run on previously acquired Mars data. The resulting localization position was downlinked but not used to update the Rover's position. The purpose of this demonstration was to gather data on the algorithm's behavior in a realistic radiation and thermal environment. While the replica Rover on Earth faithfully recreates the Rover's software and hardware, it does not simulate Mars's temperatures or radiation. This demonstration was successful and showed that it was possible to safely run global localization software in the HBS under realistic conditions on Mars. In particular, it confirmed that radiation-induced errors are infrequent and that running computationally intensive algorithms is thermally safe, despite the significantly slower heat dissipation in the Mars atmosphere.

This phase ran successfully on sol 914 (15 September 2023).

Phase 3: Closed-loop Flight Demonstration The final phase of this project includes rover flight software changes which interface between the Rover's main computer and the Heli Base Station. This will enable the rover to take a panorama of NavCam images and send data to the Base Station for processing. Then, the global localization algorithm is run, and the result is sent back to the Rover's main computer. Finally, if the result passes multiple validity checks the rover flight software updates its onboard knowledge with the new position and uncertainty, and continues driving. These checks are summarized in Figure 17.

Since this final phase updates the Rover's true position, which is mission-critical, the first test of the full global localization system will use a "shadow mode" where the updated position will not be incorporated. While the algorithm has been tested extensively on flight-identical hardware, this is done to build confidence in the overall system, including the radiation and thermal environment.

Phase 3 is scheduled to run on Perseverance in early 2024, after its RCE flight software has been updated.

Radiation hardening

Single Event Upsets (SEUs) occur when a radiation particle strikes an electronic device and causes a transient bit flip [50]. As the HBS does not have radiation-hardened components (not even ECC RAM), SEUs present a hazard for the correct functioning of the device [51].

Ingenuity is a technology demonstration and the SEU risk is acceptable for it. There have been at least 4 anomalies traced to SEUs during Ingenuity operations. For use as a rover co-processor, mitigations would have to be put in place.

Other transient radiation errors exist that may also impact the correct functioning of the HBS. One such radiation error is single-event latch-ups (SELs), which are short circuits caused by radiation creating a parasitic transistor structure known as a latch-up [50]. These can be fixed by power cycling the device. As HBS is not on for extended periods, SEL risk is minimal.

We calculate the risk of an SEU using CREME-MC, a state-of-the-art radiation effects simulation tool [52]. From these simulation results, we expect to see around 10 SEUs for 24 hours of continuous operation, assuming solar maximum. This tracks with empirical data from MSL, where we see around 1 correctable SEU in the RCE each sol.

Our approach to detecting these errors is depicted in Fig. 17. As depicted, we can detect SEUs in memory, compute, and storage. We run the algorithm twice, rebooting the Helicopter Base Station (HBS) in between the runs, and comparing both results. This reboot accounts for potential SEUs affecting the Linux kernel or critical system libraries. If the results from both runs match, we can be sure with near certainty that no SEUs have occurred in memory or in the compute pipeline.

We must also ensure that the program's input images are correct and free from SEUs. To this end, every file used as input to the software is checked with its accompanying checksum at multiple stages of the run. Additionally, output files are also sent with a checksum to ensure that the RCE receives correct information. Checksums of the global localization program are also tested to ensure it is not corrupted on disk. As the chances of bit flips modifying the program and the checksum in a way that still passes our checks are infinitesimally small, this method can ensure that the HBS storage was not affected by SEEs.

The eMMC storage chip onboard the Snapdragon 801 has dedicated vendor-supplied ECC circuits [53], but data on such circuits are trade secrets in the storage industry and thus black boxes to us. Thus, Reed-Solomon coding is also used on stored files, on top of black-box ECC hardware on storage. As Reed-Solomon is a relatively fast self-repairing code that has already been proven in rover communications, we can reduce the time to repair data stored on the HBS if an error is detected.

Localization software—We detail some of the design choices made when developing the HBS localization binary. In doing so, we aimed towards a few specific goals:

- Developing a uniform coding style that can be extended to other projects similarly making use of COTS hardware
- Minimizing developer time working on already solved or trivial issues, thus making use of as many open-source components as possible
- Mitigating radiation risks as much as possible, thus keeping binaries statically linked
- Keeping uplink sizes down due to operational constraints

Checksums on HBS use the GNU coreutils `md5sum` program.

For hash collision to occur due to radiation, where 2 files can resolve to the same checksum [54], a specific set of bits must be affected by SEUs when the checksum is run, a virtually impossible event given the built-in ECC on the eMMC chip and the design of the ext4 filesystem onboard. Furthermore, MD5 is computationally inexpensive, which has minimal

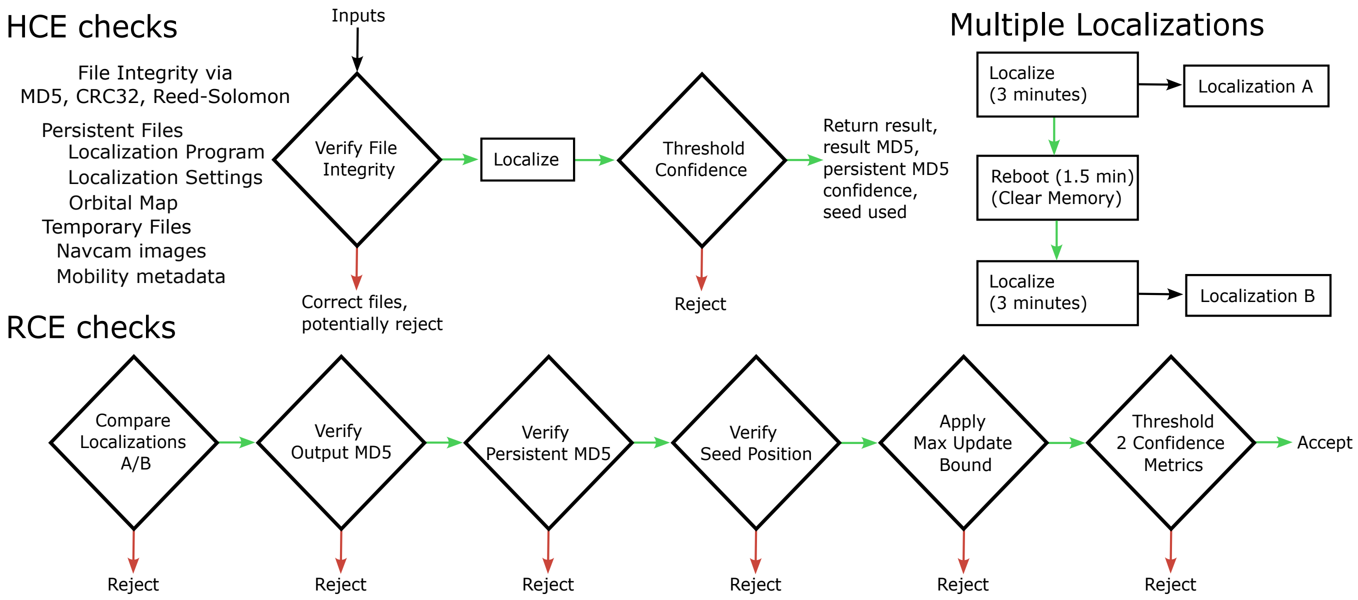

Figure 17. Checks done by both the HBS and the RCE to both mitigate radiation-induced SEUs and catch common possible localization errors. Under our probabilistic error model, the chance of performing an incorrect localization due to radiation errors is near zero. The localization algorithm itself is 100% accurate on all benchmarked data to within 1 meter (Figure 6). Timeouts (parenthesized) on each localization run catch radiation errors that may cause the HBS to stall.

impact on overall runtime.

Newer C++ standards provide memory safety and type features that are not available in older C++ standards. However, the software on the HBS is relatively outdated, with the last software update being delivered in 2017. As future missions will have newer computers with differing C++ libraries, we need a way to provide a generalized, consistent standard library for developers to use onboard the HBS.

To this end, we use LLVM, a widely-supported, open-source set of compiler tools that outputs optimized binaries from a variety of frontends, including C and C++ [55]. One key feature of LLVM is the unified intermediate representation (IR) that all optimizations are run on. By having one unified IR for all architectures, any language frontend that can be translated to LLVM IR is able to compile to any architecture. This allows us to easily cross-compile our project to a variety of targets, including x86_64 workstations as well as the ARM32 Krait architecture used by the HBS.

Another subproject of LLVM is libc++, which is a standards-compliant C++ function library built on top of LLVM. This library is separated into 2 main parts: the core library, which defines high-level C++ language features; and the Application Binary Interface (ABI), which provides architecture-specific details such as exception handling and datatype sizes. By using the system ABI, while providing our own build of the libc++ core library, we can provide developers with modern C++ features while also keeping the binary size minimal, keeping uplink bandwidth consumption low. This is due to LLVM's ability to strip unused functions, which includes *just the subset of the C++ library being used by the program* in the binary.

Rover flight software updates

Rover mobility component update—We updated the flight software running on Perseverance's main flight computer with new spacecraft commands to initiate onboard global localization and apply the results of this localization to its onboard position estimate and associated uncertainty.

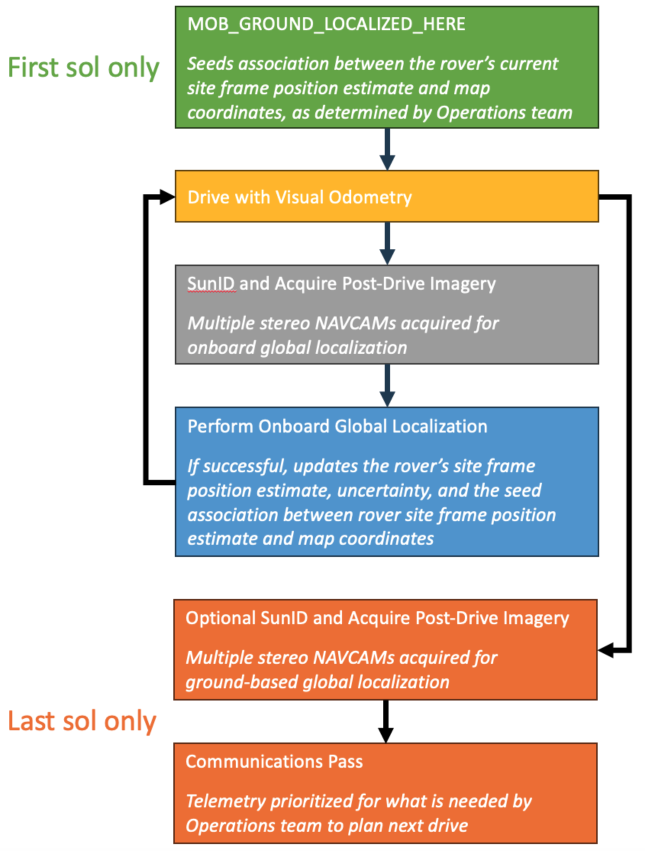

Figure 18. Global localization activities on a multi-sol plan

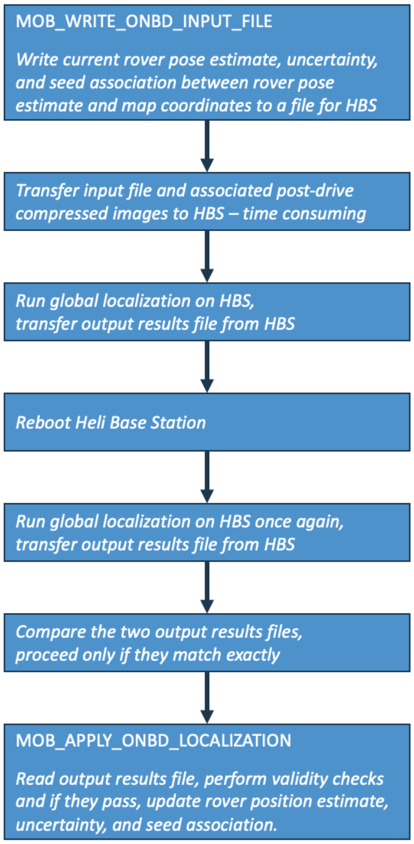

Figure 19. Steps to "Perform Onboard Global Localization"

Key new commands added to the mobility system:

- **MOB_GROUND_LOCALIZED_HERE** ***map_x map_y***
The command seeds the association between the rover's current (pre-drive) site frame position estimate and X,Y coordinates in the orbital map, based on ground based localization. This association is tracked in non-volatile memory. This command does not update the rover's position estimate, and a separate command must be used to reset to the rover's position uncertainty to zero meters.
- **MOB_WRITE_ONBD_INPUT_FILE** ***filename***
This command creates an input file for global localization that includes the current localization seed, the rover's current site frame position estimate, uncertainty, and which post-drive images to use for this onboard localization.
- **MOB_APPLY_ONBD_LOCALIZATION** ***filename***
This command receives output from the Heli Base Station, validity-checks the results of onboard global localization, and only if those checks pass will it update the rover's site frame position estimate and associated uncertainty, as well as the localization seed.

Note that while the design of the flight software and new commands do not limit the number of global localizations done per sol, the anticipated use-case is once per sol of a multi-sol drive plan, with post-drive images being acquired in the late afternoon to have rock/terrain shadows more closely match those of the orbital images that comprise our maps. Additionally, transferring NavCam images to Heli Base Station takes enough time to be prohibitive for accomplishing more than one localization per sol. The command design is flexible enough to also allow for image transfer and the localization itself to be performed pre-drive on the next sol.

See Figure 18 for an anticipated work breakdown on a multi-sol drive, and Figure 19 for the details of the steps in *Perform Onboard Global Localization*.

Whenever global localization is successful, we will want to shrink the uncertainty to the measured uncertainty from the global localization algorithm. Operators can also add margin to this for extra conservatism. Adding this as a margin term to the onboard uncertainty calculation was more straightforward than modifying the existing FSW behavior that resets the onboard odometers that accumulate distance with and without VO position knowledge to zero whenever global localization occurs.

HELO command updates to allow event driven commanding—Our initial FSW update during phase 1 was mainly to support our initial demonstration of running global localization on-board the HBS. There were three main features to implement to allow the us to perform the test without ground in the loop interaction:

- RCE to wait for event (or flag) to be set on HBS side
- Transfer arbitrarily large files to HBS
- Transfer file back to RCE without placing it in a data-product.

Normally, the Ingenuity helicopter team would trigger some action and it would not require another action from the RCE until the next ground in the loop cycle. This meant that all commanding of activities on the HBS was open loop. Our use case required adding a command to be able to signal an event from the HBS side to note when a certain action had finished. This meant setting a flag at the right time in an HBS sequence to unblock the RCE sequence and run the rest of the activity.

In addition, due to buffering constraints, when transferring large files such as FSW updates to the HBS, the helicopter team divided a single file into 50KiB chunks. Each of these chunks would be sent over and reconstructed on the HBS end. Because a single image data-product was significantly larger than 50KiB, we needed to add a command that would send an arbitrarily large file in chunks to the HBS.

Finally, when bringing files back to the RCE, we previously only had the capability to wrap files in science data-products which would ultimately be marked for downlink. Finding and parsing this file would therefore be difficult since its location would be managed internally by the RCE's data product catalog. This final command allows us to transfer a file back to RCE and place it in an arbitrary location on the filesystem.

Simulation and testbeds for efficient V&V

Safety of our software is demonstrated empirically though a series of tiered testbeds. Each testbed makes trade-offs between factors like simulation fidelity and speed. We use a tiered strategy that focuses on fast iteration times during development, and moves onto high-fidelity simulators before flight deployment, to maximize both efficiency and safety.

The most critical testbed was the SSim (Surface Simulation) software, which is the RCE flight-software-in-the-loop simulation tool used in the operations of the Perseverance rover for its activities on the surface of Mars [56]. SSim has iteration times under a minute, but does not include hardware testing, and stubs out some important aspects of the rover, such as the rover's central database, filesystem, and VxWorks.

We extended the operational implementation of SSim with a portion of the HBS FPrime flight software to help with the development of our global localization algorithms. The UART lines between the RCE and HBS were simulated to get a better idea of the file transfer duration before moving to the testbed hardware. This end-to-end test was also heavily used during our initial FSW update as it did not require testing on the hardware. This fully-integrated version of SSim is capable of performing a realistic end-to-end test in less than a minute, enabling rapid iteration with high confidence.

For testing Snapdragon code in isolation, a dedicated Snapdragon 801 was attached to a development Linux machine and flashed with flight-identical Linux. This enabled rapid and accurate iteration, but doesn't test RCE code. Similarly, there are Snapdragon flatsats which include copies of Ingenuity's communication software and stubbed RCE communications.

WSTS (Work Station Test Set) enables quickly testing only RCE software in a VxWorks simulation enviroment without hardware or HBS in the loop, and was used to validate the development of the RCE FSW update.

The highest fidelity testbed on Earth is the "Vehicle System Test Bed" (VSTB) in JPL's Mars Yard. The VSTB is a replica Mars Rover with near flight-identical hardware (including a RAD750 RCE and Snapdragon HBS) and flight-identical software, and has two similar lower-fidelity testbeds (MSTB and FSWTB). However, it takes over two hours to startup and often has iteration times measured in hours. Even with the near-perfect fidelity, it still does not capture all aspects of Mars, such as recent imagery/locations, thermal environment, radiation environment, and minor hardware differences. Accordingly, our strategy has moved to only using the VSTB for "final checkouts" before flight deployment. We have performed over 100 hours of testing on the VSTB, and often schedule our tests opportunistically when it is not in use, so that our testing has had no impact on other teams.

To retire the main risks, after having completed Earth based testing, we performed two phased deployments to Perseverance itself. By strategically scheduling these, it was possible to perform safe demonstrations while gathering additional data at perfect fidelity. For instance, phases 1 and 2 both gathered data on the thermal and radiation environments. Phase 3 will begin in "shadow mode" where global localization is performed with images taken onboard, but the results are not used onboard. They will be transmitted to the ground for analysis.

8. CONCLUSION

Our onboard global localization approach compares post-drive images against orbital maps, and achieves performance that matches manual ground based localization by human experts. It is a fundamental new capability that autonomously resets position and uncertainty knowledge after long traverses. It enables long range autonomous drives without the need for ground communication, accurate positioning after long range autonomous drives, and the ability to drive though periods that are otherwise restricted for driving.

We demonstrate how the Helicopter Base Station can be used as a fast co-processor for the rover. The protocol for communication that we developed between the rover RCE and the HBS can be extended to a number of other applications in the future.

Enables long range autonomous driving— Onboard global localization reduces rover position uncertainty. As a result, narrow drive passages remain unblocked, allowing the rover to navigate long distances even though challenging terrain. Our initial deployment of the capability on Perseverance plans to employ it after each sol of driving. As a result for a multiple-sol autonomous drive, the uncertainty will remain within a low bound (as shown in dark blue in Figure 5) vs previously when it would monotonically increase with each sol of driving without ground based localization as shown in Figure 2. In the past, if the rover needed to navigate through a narrow region, that had to occur early in the drive when the uncertainty remained small enough to enable threading the needle. As shown in the Sol 383-385 example in figure 4, when the rover encountered the narrow passage between hazards to the left and right marked by the red rectangular keepout zones, it had already been driving for two sols and the uncertainty had grown to 23.5 meters, blocking its path. After the sol 385 drive failed due to a NO_PATH fault, the rover was localized on the ground. Localization set the uncertainty to zero, the rover's path factoring in uncertainty was no longer blocked and it was able to drive another 245.37 meters on sol 386. If global localization had been available onboard, the rover could have driven farther on Sol 385, essentially requiring one less sol to cover a similar distance.

*Makes additional sols available for driving—*Global localization could enable two more sols of driving every two weeks than are currently available. A day on Mars is 37 minutes longer than a day on Earth. Due to thermal, lighting and other constraints, Perseverance is only commanded to drive between late morning and early evening on Mars. As a result, over the course of a month there are typically up to 2 week periods where it is not possible for the operations team on Earth to receive data regarding the previous sol's activity early enough to make a new plan; these lead to so-called *restricted* sols.

Often during restricted periods if there is a weekend plan which allows three sols of driving, a drive is cut short earlier in the week to allow ground based localization. Below is an example of this from the rapid traverse campaign (Figure 1):

*Sols 402–403 (Wednesday) plan uplink—*The rover was only commanded to drive on sol 402, when it successfully drove 183m. *The rover was not sent commands to attempt driving on sol 403 (Thursday)* because it would have meant that the post-drive rover panorama could not be received on Earth in time for manual ground based localization for the 404–406 (Friday) weekend plan. Driving on sol 403 would thus have resulted in not being able to drive on sols 404 and 405. Two sols of driving covers more distance than one and so this is a very typical Mars rover operations pattern for restricted sols.

*Sols 404–406 (Friday) weekend plan uplink—*The same issue repeated in the weekend plan where the rover was only commanded to drive for two sols since there was no communication pass to send data to Earth on 406 for localization. It successfully drove 260.32m on Sol 404 and 268.353 m on sol 405. *The rover was not sent commands to attempt driving on sol 406 (Sunday).*

Using onboard global localization, this strategy could continue drives even farther without having to pause every one to three sols. Over a 2 week period with restricted sols and weekends, we can potentially recover up to four additional drive sols.

Enables unlimited opportunistic extension driving—Opportunistic Extension drives [1] are a mode where human rover planners extend the plan from the previous sol's autonomous drive without knowing where the rover will be. This approach was used on sols 407–409. Drive plans were uplinked on sols 407, 408, and 409, but on each later sol the rover planners did not know where the rover would be since data from the previous drive was not yet available. Each new plan must be robust to the rover being anywhere along its previously-commanded path. This strategy succeeded in achieving the longest 3-sol drive distance yet, 700 meters during sols 407–409. But it is fundamentally limited by position uncertainty growth, which narrows corridors and grows any hazards labeled as Keepout zones. We do not expect to be able to extend these plans for more than three sols before immobilizing the rover during a restricted sol while we await Earth-based localization and start anew.

In the example from rapid traverse in the previous section, the rover only drove on the first sol of the 402–403 plan, and the first two sols of the sol 404–406 plan. It performed the longest possible extension drive over sols 407–409. With onboard global localization the driving over sols 402-409 could have been done in two fewer sols if planned as one opportunistic extension segment of 1.41km including driving on the skipped sols 403 and 406. The entire 5km rapid traverse campaign could have been planned as an opportunistic extension drive with onboard global localization.

Global localization will enable extending drive plans arbitrarily, without humans ever knowing where the rover would actually start. This could completely change the paradigm for driving on Mars missions like Perseverance. Rover planners will set new waypoints to extend the drive with every communication opportunity, and the rover will use all drive time available to follow the waypoint "breadcrumbs." There will be no need to prematurely terminate drives with margin for communication passes. Thermal and power constraints will still be respected. During Mars conjunction, when the Sun is between Earth and Mars limiting communication with the rover, the rover is typically not driven for a three week period. Opportunistic extension drives could enable commanding a drive over that entire period.

Driving faster to next target of interest will result in more time spent on science and less on engineering activities. It will add robustness to the planned Mars Sample Return architecture as the rover will be able to traverse long distances over a short period of time, for example to a SRL rendezvous location, or to perform science walkabouts and sorties from safe landing locations.

Allows more flexible operations staffing—With opportunistic extension drives, rover planners extend the previous sol's autonomous drive. This paradigm allows planning of multiple sols of opportunistic extension drive for any given uplink depending on the complexity of drive planning. For example, if the operations team had planned the entire 407-409 drive in just the 407 uplink then operations staffing for sols 408 and 409 could have been on call or skipped, allowing staff to perform strategic work or take a break over a holiday period.

Enables accurate positioning after long AutoNav drives—After long AutoNav drives the rover position uncertainty can be large (see Figure 2) and therefore there is no guarantee the rover will be in the desired location for mid-drive science observations. If a science observation is desirable, the drive can be terminated early to allow a more precise short drive the next sol to the location of interest, or the observation must be skipped. The onboard global localization paradigm could be extended to perform global localization at the end of a drive, and if the rover were more than the maximum desired offset from the location for performing the mid-drive remote science observation, another segment of driving could be performed to get to within meters of the observation location. After performing mid-drive observations, such as with SuperCam (potentially with AEGIS [2] in a specific area of interest), Mastcam, or RIMFAX, the rover would continue driving. This will enable more science observations since drive distance will not have to be traded for science.

Demonstrates the use of the HBS Snapdragon as a rover coprocessor—The presence of the more capable HBS Snapdragon 801 co-processor is what made it possible to consider deploying capabilities like onboard global localization. Phase 2 of global localization ran completely onboard the Perseverance rover on Mars in only 32s. In addition, use of an isolated co-processor limits the scope of any errors to its results, reducing risk and impact to the overall rover mission. Development on the HBS is also not restricted by existing rover RCE flight software practices. The combination of the radiation hardened RAD750 and the HBS Snapdragon allows performing separable software based radiation mitigations. For surface science missions, running the process multiple times is a very reasonable option since it is so fast and the localization activity does not have real time constraints.

Lessons Learned

Design rover flight software with components—Perseverance Rover Compute Element flight software was designed from the outset with a mobility component load mechanism which enabled it to be updated without requiring a full flight software update [57]. The results from running global localization on the coprocessor needed to be read by the rover flight software to update position. A full flight software update would have required a substantial amount of review and retest, even on modules that were not modified. However, flight software components impact only a small subset of modules, can be loaded individually, and therefore do not require a full flight software update.

Invest in benchmark dataset— One of the reasons global localization was selected as the first application to test the approach of using HBS as a coprocessor is because ground based manual localization had been performed since the beginning of the mission and this data existed in a database. Early investment was made on developing this ground truth benchmark dataset. The reliable ground truth with real Mars panoramas enabled fast technology development iteration with no impact on the ongoing mission. Almost all the core onboard global localization technology development was performed over a two month period in the summer.

Software simulations and lightweight testbeds enable fast turnaround— The ground software simulation, SSim [56], was augmented to include the helicopter base station for early simulated testing. The ability to test end-to-end between RCE and HBS on a desktop workstation in less than a minute also enabled rapid iteration. SSim is used in operations to validate every plan uplinked to the rover. Testing in the same environment helped develop operations products that were very mature. For testing performance of the code for HBS a dedicated Snapdragon was attached to a development Linux machine.

Slow communication between the rover computer and a fast coprocessor poses challenges—The HBS was intended for communication with Ingenuity which was a technology demonstration. The serial link between the RCE and the HBS is fixed at 10KB/s, a rate originally intended to reduce impacts to the RCE's processing. This communication bandwidth posed a number of challenges for its usage as a rover coprocessor. When considering coprocessors for a mission designing them with high communication bandwidth where possible will allow for a lot more flexibility in future use.

Develop and deploy in phases to reduce risk and limit impact—Much of the development was done over two summers with interns. From the beginning we planned for three distinct phases of deployment to flight. Each focused on retiring one of the main elements of risk as fast as possible. Phase 1 demonstrated that global localization could be sandboxed on the HBS from HBS flight software. Phase 2 demonstrated the performance of global localization software in isolation on the HBS, all the data including the rover panorama were from a previous position and sent from the ground. Phase 3 will first be performed in shadow mode where we take rover panoramas on the rover and transfer them to the HBS and run global localization, but send the results to the ground without updating the rover pose. After we have tested the accuracy and performance of the results it will be fully deployed. The phases also served as a mechanism to help focus and reprioritise if challenges were encountered.

Long lead time for Ground Data System (GDS)—Although flight software is designed as a component and does not require a full flight software update, GDS follows the same process for the command dictionary update for a component as for a full flight software update. This process can add a long lead time. The Software Delivery Review (SDR) for the rover's RCE fight software, which provides the software release to GDS, was on September 25, 2023. However, the GDS updates that allow the component load to occur in flight are not estimated to occur until spring 2024. Methods for building in spare command and telemetry capability ahead of time may enable shortening this delay in the future.

Future Work

The approach presented in this paper could be used for onboard global localization for Lunar rover missions such as Endurance. It could also be used for automated ground based localization by Lunar rover missions that may have limited onboard processing, but do have bandwidth to transmit panoramas to the ground. It could be augmented for aerial applications as well.

Our sandboxing environment shows that HBS can be used as a coprocessor for other rover applications as well. Prime among these is eliminating the ground in the loop cycles needed for placing arm turret-mounted science instruments PIXL and SHERLOC safely into an abrasion patch. A process that currently takes 4 sols could be reduced to 2 sols.

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BIOGRAPHY

Vandi Verma *is the Deputy Section Manager for Mobility and Robotics Systems at NASA JPL, and the Chief Engineer of Robotic Operations for Mars 2020. Robotics capabilities she has worked on are in use on the Perseverance, and Curiosity rovers, and in human spaceflight projects. She worked on the Mars Exploration Rovers and Ingenuity helicopter Technology Demonstration. She led the onboard global localization effort.*

Jeremy Nash *is Group Lead of the Aerial and Orbital Image Analysis group at the Jet Propulsion Laboratory. His recent work includes creating Mars maps for the Sample Retrieval Lander (SRL) Entry, Descent, and Landing (EDL) system, and global localization for the Perseverance rover.*

Lucas Saldyt *is a Graduate Engineering Intern at the Jet Propulsion Laboratory. He is responsible for research, development, integration, and testing for Global Localization using the Heli Base Station. He is a Ph.D. student at Arizona State University, where he researches neurosymbolic programming for robotics.*

Quintin Dwight *is currently an undergraduate student at the University of Michigan, Ann Arbor, majoring in Computer Science and minoring in Mathematics. He is software lead (and was perception lead) for the Michigan Mars Rover project that won the University Rover Challenge (URC) and Canadian International Rover Challenge (CIRC).*

Haoda Wang *is a Ph.D. student at Columbia University researching methods for software-only radiation hardening on COTS computers. Previously, he has worked on flight software simulations on Mars 2020, and developed a fuzzer that has caught multiple flight software bugs. He is also a 2022 DoD NDSEG fellow and a 2021 Goldwater Scholar, and holds a BS in Computer Engineering and Computer Science from the University of Southern California.*

Steven Myint *is a Group Lead in the Robotics section of the Jet Propulsion Laboratory. His recent work include developing flight software for the Mars 2020 rover, applying modern software fuzzing techniques to finding problems in safety-critical flight software, leading the development of SSim (Surface Simulation), the primary simulation tool for Mars 2020 and Mars Sample Return operations, and leading the development of RSVP (Robot Sequencing and Visualization Program) for Mars 2020. In Mars 2020 Robotic Operations, his roles include Rover Planner and Helicopter Integration Engineer.*

Jeffrey Biesiadecki *is the M2020 Sampling and Caching Subsystem flight software lead as well as a developer of M2020's mobility flight software including the Thinking While Driving design which enables continuous driving by acquiring and processing images during motion. Jeff also developed motor control and real-time mobility flight software for MER and MSL rovers, has been a rover driver on MER, MSL, and M2020, and has also served as Chief Engineer for the Mobility and Robotics Systems Section at NASA's Jet Propulsion Laboratory.*

Mark Maimone *is Mars 2020 Robotic Operations Deputy Team Chief, member of the Rover Planner and FSW development teams, and a Robotic Systems Engineer in the Robotic Mobility group at the Jet Propulsion Laboratory. Mark designed and implemented the GESTALT self-driving Flight Software for the MER and MSL missions, and contributed to the Mars 2020 ENav self-driving Flight Software; during MSL operations served as Deputy Lead Rover Planner, Lead Mobility Rover Planner and Flight Software Lead; and developed downlink automation tools for MER and MSL. Mark holds a Ph.D. in Computer Science from Carnegie Mellon University, and has also developed navigation and image processing capabilities for robots in Chornobyl and the Atacama Desert.*

Andrei Tumbar *is a Robotics Engineer at the Jet Propulsion Laboratory. He works on simulation and operations tools for various missions including the Mars 2020 Perseverance Rover, Ingenuity Helicopter, MSL, and COLDArm and CADRE. In addition to simulation, he designed the compiler infrastructure around the NPM Direct tool as well as built a multi-mission platform for simulating FPrime based flight software. He is currently leading a project to efficiently simulate the Ingenuity helicopter for use in operations.*

Adnan Ansar *received a BA (1993) in Physics, MA (1993) in Mathematics, MS (1998) in Computer Science and PhD (2001) in Computer Science all from the University of Pennsylvania, with the last earned at the GRASP Laboratory. He has been a member of the Robotics Section at NASA's Jet Propulsion Laboratory (JPL) since 2002. While at JPL, his research has included work on image-based position estimation, camera calibration, stereo vision, structure from motion, multi-modal data registration, and orbital mapping for terrain relative navigation.*

Gerik Kubiak *is a Robotics Technolgist at the Jet Propulsion Laboratory. He works primarily as a flight software developer, supporting the Sample Recovery Helicopters, COLDArm, and Ingenuity, where he is the flight software lead. He has also worked as a systems engineer support the Mars 2020 Robotic Arm.*

Robert Hogg *is a Senior Systems Engineer at NASA's Jet Propulsion Lab in Pasadena, California. Robert began his career at NASA in 1997 as a flight software engineer on the Deep Space One spacecraft, which tested 12 advanced high-risk technologies in space and returned priceless images of Comet Borrelly. Robert is currently the Deputy Mission Manager and Helicopter Manager for the Mars 2020 mission. Prior to his work on Mars 2020, Robert developed systems and behavior software for the JPL Urban Robot, concluding with a successful robotics system that could navigate complex terrain and climb flights of stairs autonomously. Concurrently he created the Spiderbot research task, which investigated adaptable sensor webs and mobility for small legged robots. Robert has extensive experience in flight systems design and development, and planetary operations in the areas of robotics and navigation from his seven years of work on the Mars Science Laboratory mission, and its Curiosity rover, which landed in 2012 and is still exploring mars to this day.*