Practical Operational Readiness Gambits: Operations Training Simulations for the Curiosity Rover

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Abstract—**The Mars Science Laboratory team had been putting in effort to make a Training Venue to allow for parallel shadow tactical operations for trainees to actively work alongside the prime tactical operations personnel without affecting operations, since staffing constraints and shortened operations timelines were straining the tactical process in supporting operations trainees in the traditional way. The COVID- 19 Pandemic presented further challenges in continuing on-console training for MSL operations trainees. The MSL operations team switched to fully remote operations, thus hampering the direct mentorship a trainee would normally receive while on site at JPL. The Mars 2020 training team had developed a concept for rover operations training simulations based on Johnson Space Center's extensive simulations training program for astronauts and flight controllers. The MSL team borrowed this idea, and implemented these training simulations which are called Practical Operational Readiness Gambits (PORGs). The PORGs so far have focused on the Science Planner and Rover Planner roles, which are two crucial roles in tactical operations that engage in key interactions throughout a shift. PORGs are based on actual sol scenarios that have occurred on Mars and follow the tactical operations process and timeline as closely as possible. However, unlike an operations shift, PORGs can slow down or pause to allow for more mentoring time. PORGs can focus on particular skills to test the trainees on their understanding of a concept. PORGs increase in complexity with each scenario to ease the trainees into more typical tactical operations workloads. As more trainees join the MSL operations team, more roles are being incorporated into PORGs. There are plans to incorporate certified operations personnel into PORGs to practice anomaly response situations. PORGs have become an essential part of the MSL operations training program and will continue even after the return to on-site operations at JPL.**

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1. NOMENCLATURE

APXS	Alpha Particle X-Ray Spectrometer
CCAM/ChemCam	Chemistry and Camera instrument
DRT	Dust Removal Tool
ECAM	Engineering Cameras
EUL	Engineering Uplink Lead
JPL	Jet Propulsion Laboratory
MAHLI	Mars Hand Lens Imager
MSL	Mars Science Laboratory
NASA	National Aeronautics and Space Administration
PDI	Post-drive Imaging
PORG	Practical Operational Readiness Gambit
PUL	Payload Uplink Lead
RMOTS	Rover Mission Operations Training System
RP	Rover Planner
sol	Martian day
SPaSIE	Science Planner and Sequence Integration Engineer
SP	Science Planner
SIE	Sequence Integration Engineer
SPS	Surface Properties Scientist
TUL	Tactical Uplink Lead
VO	Visual Odometry
VPN	Virtual Private Network

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2. INTRODUCTION

Human spaceflight programs have been training flight operations personnel with simulations for decades, while Mars rover operations has typically employed apprenticeship- style training methods with tactical operations shadow shifts. With COVID-19 Safer at Home orders in March 2020, the Mars Science Laboratory (MSL) team switched to a more challenging remote operations [1], forcing some limitations on trainees in operations. Even before the pandemic, the MSL team was seeking solutions for the reliance of on-console training, as staffing constraints and shortened operations timelines were straining the resources available to properly train new operations personnel. Meanwhile, the Mars 2020 training team had begun formulating operations training simulations, motivated by a need for a more rapid training process with fewer on-console training opportunities. Given the shared personnel between MSL and M2020, the MSL team was able to implement the training simulations concept quickly with a focus on the remote operations environment. These new training simulations are called Practical Operational Readiness Gambits (PORGs), and allow for the hands-on training of new operations personnel in this drastically different environment without disrupting remote tactical operations.

Section Three describes the training philosophy and history of the Mars rover training programs. Section Four describes the details of PORGs and their development from previous training programs. Section Five describes the Training Venue development along with other software considerations. Section Six outlines the implementation of PORGs as well as the selection of training scenarios. Section Seven includes

lessons learned so far. Section Eight describes the future of PORGs and planned work to go.

3. Training Philosophy for Mars Rovers

Several generations of Mars rover operations teams have trained via an apprenticeship with hands-on shadow shifts while actively involved in rover operations. Role training can also include one-on-one discussions, reading of background material and procedures, classroom sessions, and homework assignments. While shadow shifts can slow down the operations timeline, it is a valuable experience which the Mars rover projects consider worth the cost. Shadow shifts make up most of the training program, as trainees receive interactive mentorship with certified personnel and are exposed to all aspects of planning and role interactions. The dynamic nature of activity planning and sequencing on operational shifts is difficult to convey and teach in a classroom environment, and thus is better experienced first-hand. However, simultaneously learning the technical skills required as well as becoming familiar with the operations environment can be challenging. The tactical operations environment requires the ability to manage multiple real-time inputs from multiple sources, all while under a time pressure to meet a command readiness deadline [2] [3] [4] [5].

Fortuitously, Mars 2020 had been working to make simulations a more integral part of training. The early design of the Mars 2020 Training System coincided with the MSL extended mission training re-configuration. On the Mars 2020 mission, the ambitious surface mission objectives requires an increase in pace of operations, even compared to MSL, that relies a fully trained and productive team right at landing. In order to achieve that level of training, the Rover Mission Operations Training System (RMOTS) needed to establish effective, efficient, and maintainable training. RMOTS conducted a market survey as well as canvasing NASA centers for industry best practices on which to build a training approach. The survey found that the use of training simulations is a keystone of successful training systems that do not rely extensively on shadow shifts. RMOTS had to look no further than NASA's Johnson Space Center and the astronaut training program for mentoring and guidance in crafting and integrating training simulations into the Mars 2020 planned methodologies. The PORG concept, while not yet implemented in the Mars 2020 training program, has become an essential part of the MSL training program.

The MSL PORGs present an opportunity to increase the depth and breadth of training scenarios that a trainee may not experience as a shadow. Traditionally, training consists of technical knowledge acquisition and on-shift experience. However, with a complicated and dynamic rover system, not all scenarios can be experienced while on shift. Some activities only occur every several hundred planning cycles, which can limit the depth of exposure any individual trainee may face. The PORGs allow us to capture more of these situations, and not limit trainee exposure to only discussion or individual practice but to a near-tactical like environment.

Prior to the PORGs, there was no other way to experience the many facets of a genuine tactical rover operations environment aside from shadow shift participation. All operations personnel must satisfy multiple complex scientific and engineering constraints in a time limited environment while interfacing with dozens of other personnel under similar constraints. Remote work supports fewer traditional tactical shadow shifts and less opportunity for hands-on training due to the heightened complexity of remote planning. With the limitations imposed on shadow shifts during remote operations, the PORGs have become an essential part of preparing the trainees for operations certification. With a PORG, tactical requests and complications can be simulated in a typical tactical time frame. Key interactions with other personnel can be practiced which otherwise would only occur on shift and may only occur occasionally. Another benefit of PORGs is that it can be slowed down or paused to address questions and mentor the trainees, which is limited on an operations shift due to timeline constraints.

4. What is a PORG?

A PORG follows the MSL operations process as closely as possible, given tool limitations and personnel participation. Currently, the trainees do not practice the entire tactical planning cycle. This is partially due to where trainees are in their learning timelines and partially because the tool suite has not been fully adapted to allow for all parts of the process to be exercised. The tool adaptation issues are discussed more in the Section Five. The most dynamic parts of the activity planning process are simulated in PORGs, and the non-simulated portion of sequence review and delivery is heavily automated but remains a desired exercise for future PORG development. A portion of the tactical timeline is shown in Figure 1. Currently the SP participates in a PORG until the Activity Plan Approval Meeting and the RP participates through Master Submaster Walkthrough with partial practice of sequence delivery, thus encapsulating much of the tactical timeline. PORGs do not currently simulate the remainder of the tactical day, the downlink tactical process, or the supratactical process.

Not all operational roles are currently participating in PORGs since they do not have current trainees. The PORGs have mostly focused on the trainees for the Science Planner (SP) and Rover Planner (RP) roles. The Science Planner works to build the tactical activity plan that models the scientific, engineering, and robotic activities of the Curiosity rover. The Rover Planners are responsible for the robotic arm and mobility operations of the Curiosity rover. PORGs also require the PORG herder role. There is one PORG herder per role participating, and they guide the trainees. PORG herders are often involved with its initial preparation.

Rover Planner Training Program

The Rover Planner training program is fairly comprehensive and in-depth, given the breadth and depth of knowledge an RP must have to safely operate the rover. The program starts with mobility classes and homework, followed by approximately 20 hands-on lab activities for traverse practice, another set of arm classes and homework, and approximately 20 hands-on lab activities for arm and contact science practice, along with approximately 5 hands-on lab activities to practice drill activities. These hands-on labs give trainees practice by re-planning a previous sol plan in the form of a drive or arm activity. The initial PORGs were selected from later labs, so trainees still gained experience in earlier labs on developing the RP activities in a self-driven environment without the pressure of tactical operations. This helps practice with the operations tools and allows time to dive into the extensive rover documentation. A PORG introduces some time pressure and trainees gain experience of preparing for and presenting at various tactical shift meetings.

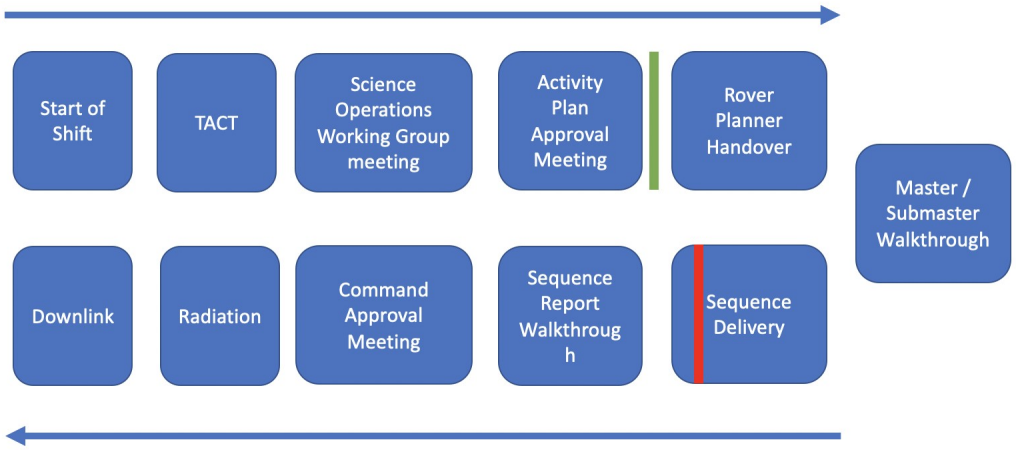

Figure 1. Tactical Timeline Overview for PORGs. Green line indicates end of SP participation and red line indicates end of RP participation.

The activity planning portion of the day is incredibly dynamic and every sol's plan has different constraints. Examples of tactical challenges that are faced by the RPs on a regular basis include things such as arm configuration changes between contact science targets, particularly dangerous terrain with rock hazards to avoid while traversing, and more. There is also a time management and triage aspect that has to be learned to be successful on tactical. On every contact science plan, the science team members will approach the RPs to assess potential contact science targets, but they may suggest five or more targets when the plan can only accommodate two. The RP trainee has to learn how to triage those potential targets, distribute target analysis work to the other RPs present, and learn how to communicate with the science team about the best contact science targets to achieve the science goals of the plan. Another example is the science team can suggest a rock in the distance for the drive to end at to potentially perform contact science on a future plan. The RP trainee has to learn how to assess traverse uncertainty by understanding potential slip risks, mesh noise, positional uncertainty, and other factors. While topics like the arm configuration changes can be covered in labs, the dynamics of having to assess targets while interacting with the science team is something not easily conveyed in a solo activity.

Science Planner Training Program

The Science Planner and Sequence Integration Engineer (SPaSIE) requires a comprehensive understanding of the rover. The SP fields all requests from the Science Operations team, the Engineering Operations team, and the Rover Planners, and then works to accurately and safely implement those requests into a tactical plan. The SP also communicates any limitations such as power or data volume constraints, any safety concerns, or any complexity issues and assists in creating solutions. SPaSIE training involves reading technical documentation, participating in academic discussions, as well as on-console experience. The SPaSIE team maintains a detailed training checklist of common and uncommon concepts, scenarios, and issues a trainee may face. In addition, there are requirements to demonstrate proficiency and understanding of multiple concepts while on-console in addition to discussions with certified SPaSIEs. PORGs were structured such that a trainee would get exposure to many different situations, some of which are uncommon to experience in an actual tactical environment.

The tactical environment is similarly complex and dynamic for the SP. For instance, on a weekend 3-sol planning day with contact science and a drive, the SP works to integrate science team requests into the plan as well as appropriately model RP arm and drive activities into a plan. An initial skeleton plan has been created in the preceding days, and it contains a rough draft with placeholders of all activities that may be desired in the following plan. The skeleton plan can change due to new science interests or in response to any number of technical challenges discovered in the downlinked data from the previous sols' activities. The SP works with this skeleton, or quickly creates another in the latter case. Initial resources, such as power or data volume limitations are analyzed. As the day progresses, science team members deliver activity fragments that the SP integrates into the plan. For a contact science sol, there are a number of targeted science observations requested. The SP should correct any issues with those activities and advise on when the number of science requests surpass the time originally allotted in the plan. Often, the SP can also optimize activities and increase the number of science activities and observations that are possible in the plan. With contact science there are several sets of arm activities. While the RPs work on the specific sequencing for those activities, the SP must represent those activities in an accurate manner in the plan so that the timing, power, and data volume are correctly modeled and in a way that clearly and concisely captures the RP sequencing. The above integration occurs with the SP maintaining plan limitations and avoiding any rover safety issues or concerns. The work is done in cooperation with all science and engineering representatives and in full view of the tactical operations team. This allows for dynamic changes and requires quick implementation in order to maintain the tactical timeline.

5. Venue Development

In the years prior to the creation of the PORGs, the SPaSIE team was working to improve the software tool options available for training. The MSL operations team executes tactical on the Operations Venue, which is exclusively for tactical operations work. Training is done on a separate Training Venue that features a tool suite that is similar to what is available tactically. The existing Training Venue allowed SPaSIE users to practice portions of the tactical process in a software venue disconnected from the tactical Operations Venue. Technology

improvements have made storage more affordable, allowing for a dedicated Training Venue populated with data despite design limitations earlier in the mission.

In order to increase the exposure of trainees to the tactical process while also not impacting or delaying the tactical process, a Training Venue machine was setup within the tactical operations room. This allowed for "parallel operations" for trainees; they could hear the numerous requests, questions, optimizations, and problems the on-console SPaSIE was fielding in often a very time-constrained environment and apply those changes to a separate test-tactical plan of their own.

A process had been developed in order to allow the Training Venue to access intermediate products from the Operations Venue without impacting the Operations Venue itself. This process allows for a tactical-like execution of a PORG with all requisite input products present. With remote work, additional preparations needed to occur with VPN setup, remote access tools, and web conferencing applications.

One key need was replicating the tactical console trade-off that occurs in a typical tactical training shift. Oftentimes a trainer may need to step in to demonstrate a particular concept or to step in entirely for a portion of the tactical process. As remote users are not co-located, this required a remote desktop that allows multiple users to simultaneously share one desktop, allowing for a fluid transition between trainer and trainee.

The Rover Planner tool and software suite is heavily reliant on a backend interaction that is currently only on the Operations Venue. Instead of operating on the Training Venue, the RP trainees must work in a special non-tactical directory structure on the Operations Venue. Even a basic tool such as posting screenshots was not compatible with posting to the Training Venue tactical reports website, so significant effort is ongoing to update the RP tools and software to interact with the Training Venue. The Sequence Delivery script structure is actively being updated to be able to deliver RP sequences from the Operations Venue to the Training Venue, which will make the SIE-RP interactions planned in future PORGs more meaningful. RPs are able to use desktop client versions of the planning software to interact with the SP plans that are developed in the Training Venue during PORGs.

6. IMPLEMENTATION

The PORG implementation on MSL happened quickly. This was possible due to the significant process development of the Training Venue in the years prior. The concept had been well explored by the Mars 2020 training team and two-thirds of that training team also support MSL operations so they were able to leverage their experience. JPL began mandatory work from home on March 17, 2020 and the first PORG occurred April 9, 2020. The current cadence is once per week, but given the current sets of trainees, a scenario is run twice so all trainees get a chance to experience each scenario.

While most of the PORGs have focused on SP and RP trainees and their interactions, later PORGs have also started to include the Engineering Uplink Lead (EUL) and Tactical Uplink Lead (TUL) trainees. A TUL trainee was included in a drive anomaly recovery PORG, so their ability to handle anomalies could be assessed before role certification. The earlier PORGs also included practice of assessing rover stability, using the Slip Risk Assessment Process (SRAP). While normally this is not a task performed by tactical RPs, it was included for the RP trainees to practice in the first few PORGs. This extra practice helped expedite their strategic RP certifications. SP trainees are also able to interact with the RP trainees in refining arm and drive activities, which is an important part of the SP process. SPs are able to practice with unusual plan structure such as arm anomaly recovery activities or other uncommon constraints such as a severely limited downlink data volume pass in PORGs.

Currently, PORG scenarios are selected based on the trainee skills to be tested or practiced during the PORG. The current RP trainees had no on-site tactical experience, as their first shifts were to occur in April 2020. As a result, the first PORG scenario was a relatively simple traverse plan, so the focus was in introducing trainees to the remote tactical process. SP trainees had some shadow shifts prior to the change to remote operations, but were limited in their ability to effectively practice. Once the RP trainees had completed their arm coursework and a few independent homework assignments and labs, arm activities were implemented in the PORGs in addition to drive scenarios. Each scenario is progressively harder for RP trainees, with additions such as more complex terrains to traverse over or rocks that violate some arm activity constraints. Challenges increase for the SP trainees as well, with PORGs featuring more complex science requests and RP interactions. Table 1 describes the first ten PORG scenarios. With the current group of trainees, there is an RP trainee who is also a TUL trainee. There was a desire to see trainees react to an anomaly scenario so two versions of PORG ten were developed so the trainee was able to experience an anomaly as both an RP and a TUL trainee. Initial considerations of PORG scenario selection require an appropriate level of difficulty for the trainees, a suitable terrain in the robotic arm workspace, and additional complexities for the SP. In addition, PORG scenario developers sought plans that would allow PORG herders the ability to introduce additional challenges that may not have been faced tactically on this specific sol such as a late change of a contact science target or the inclusion of a new science observation such as a ChemCam AEGIS activity.

After a specific scenario has been selected to make into a PORG, a template page is filled out with the specific information about the sol scenario. This allows the PORG herders to have the information which will be provided to the trainees throughout the simulation. The PORG herders must play-act all the other roles that are normally on shift that interact with their respective role that are not participating in the PORG. For example, a critical interaction for the RPs is with the Surface Properties Scientist (SPS). The SPS helps provide scientific perspective on the types of terrains safe for the rover to drive over. The SPS report from that particular sol is copied into the PORG template, so the PORG herder knows what guidance was given for that traverse. The certified RP also has experience interacting with the SPS, so in cases of limited report information, they can pull from their experience and play-act the SPS. Similarly, Science Planners interact with individual instrument representatives, science theme groups, other science leadership, along with engineering representatives. As PORG herder, each of those roles along with any limitations of knowledge each may individually have, must be represented for an effective training simulation. In a short period, the PORG herder may request more science activity time, ask as an engineering representative to fix an activity problem, and then also play-act as the TUL in requesting information on plan resources. The template page also

Table 1. Selected PORG Scenarios. Considerations identify expected challenges at a high level for the PORG in question.

PORG	Sol(s)	Participating Roles	High Level Plan Description	Considerations
1	1282	RP, SP	Drive along strategic route	Difficult terrain, CCAM collision checks, PDI
2	976	RP, SP	Drive towards a science goal	Cross-slope and sandy driving
3	1042	RP	Precision approach to a science target	Intro to Target Manager, Arm retract and stow
4	2694-2695	RP, SP	Precision approach to science targets	Imaging while driving, high-slip traverse
5	2090-2092	RP, SP	Drive along strategic route	High-slip traverse, approach CCAM target spot
6	2027-2028	RP, SP, EUL	Drive along strategic route	Relocalization of old meshes to extend drive
7	2434-2435	RP, SP, EUL	Touch and go	Arm and drive, VO, approach ridge imaging spot
8	2731-2732	RP, SP	Touch and go	Full MAHLI wheel imaging, APXS prox mode
9	2696-2698	RP, SP	Touch and go	Multiple arm targets, DRT, MAHLI mosaic
10 (v1)	2802	RP, SP	Drive to strategic route from detour	Drive fault recovery
10 (v2)	2052	RP, SP, TUL, EUL	Drive towards a potential drill target	Drive fault recovery

includes the working directory paths, starter activity plans, any workarounds for scripts or other process points that have not been fully adapted for PORGs, a list of items to throw at the trainees to increase complexity as desired, and the reports of any relevant roles that must be play-acted by the PORG herders.

Based on the PORG experiences, both SP and RP trainees gain valuable experience and practice. SP trainees initially observed remote tactical without interacting with the on-console SP. With the addition of PORGs and additional remote operations capability expansions, SPs were able to start shadowing remote operations in April 2020. RP trainees were allowed to start shadowing the remote MSL operations and performing RP activities on shift in August 2020.

7. Lessons Learned

PORGs have helped the MSL team identify weak points in the training program. The RP classes have been updated to include more information about the operations process and activity planning to help in preparation for the PORGs and eventual tactical shadowing. Tool trainings have been updated to cover processes used in operations that were not previously covered in the tool training exercises.

The PORG herders started as just one person for each role, but after a month, was expanded to rotate in other certified personnel, from recently certified to heavily experienced. Every PORG herder has their own experiences and brings diversity in tactical approaches taken, so by diversifying the mentors, the trainees get a greater understanding of the respective training roles. This variety of mentors will simulate what operations personnel face in actual tactical operations.

The RP tools are heavily reliant on the actual Operations Venue due to tool interactions which have not been ported over to the Training Venue. For example, the strategic RPs evaluate rover stability with SRAP at the start of every shift where arm activities are planned, but the SRAP script was only checking current operational data, so the SRAP manual process had to be exercised. Many scripts were later identified as not having to be venue dependent and made to allow for posting and/or interacting with the Training Venue, which over time, has allowed for more accurate simulations of the tactical process. However, there is still work to go and some tools may prove to take too much effort to make compatible with the Training Venue and will require workarounds.

The duality of RPs on the Operations Venue and SPs on the Training Venue ended up excluding the Engineering Camera Payload Uplink Lead (ECAM PUL) trainee from using the PORGs for training. The duplication of effort to develop and deliver sequences for the RPs to test on the Operations Venue while interacting with the SPs plan on the Training Venue made the PORG process too different from normal tactical operations to be a useful training exercise for an ECAM PUL trainee at this time.

The SP role features many interactions with personnel of varying specialties. It's important to develop the skills to recognize and solve an issue, but also to understand who is capable of correctly and accurately responding to a query. With remote operations, a trainer has far less insight into how a trainee is handling tactical pressures so far more explicit communication is needed between the trainer and trainee for proper assessment.

Often, the play-acting for other roles is done by personnel who are not certified in performing those roles. Now as part of the PORG template, a "script" is added in order to guide the PORG herders in how to lead the tactical meetings. This script is based on actual tactical checklists and procedures for those roles. However, much of the play-acting is fed via the tactical experience of the trainer.

8. The Future of PORGs

As new classes of trainees join MSL, the PORGs will adapt to include new roles. Every PORG scenario has been saved, so future sets of trainees can experience the same challenging scenarios in preparation for their tactical shifts. A new TUL trainee joined the PORGs in October 2020 to gain more experience, in particular with personnel and timeline management. There will be a new class of EUL trainees and RP trainees starting in January 2021. The new EUL trainees will join the PORGs while current RP trainees will phase out into only tactical shadowing while the newer RP trainees will take their place. The SP is already a role participant, but as the SP continues along their training pipeline to become an SIE, PORGs will be adapted to include them. While in nominal planning, the SIE may face limited challenges due to heavy automation, so issues are uncommonly experienced by a trainee on tactical operations. PORGs are invaluable for experiencing those uncommon scenarios, so this requires additional Training Venue development. Development continues to port more scripts and update other tools to be compatible with the Training Venue, such that other roles can more easily join PORGs and allow for higher fidelity simulations for currently participating roles.

Based on the extended remote operations time, a new RP training pipeline has been proposed that fully incorporates PORGs into the training baseline and requires at least ten

PORGs before participating in tactical shadowing. This will continue after returning on-site at JPL given the positive impact of preparing trainees for operations.

There is an intention to make PORGs that cover anomalous scenarios and have both trainees and certified personnel practice responding to off-nominal behaviors. Since major anomalies are rare and often require more manual workarounds in tools and scripts, the intent is to practice those off-nominal procedures. In addition, response to anomaly situations may not have quick and readily available solutions. By practicing these situations, trainees would learn the skills and certified personnel would be refreshed on how to provide reasonable assessments, know the relevant cognizant engineer(s) to contact, and understand what resources are available in the event of an actual anomaly.

9. CONCLUSIONS

PORGs are now an essential part of the training program for the MSL operations team. The PORGs have allowed for continued training of key roles of the tactical process that would have otherwise been slowed down or stalled by the transition to remote operations. They allow for a deepening of existing training and exploration of more uncommon scenarios. PORGs also meet a key need of simulating multiple tactical role interactions and the time limitations which are otherwise only met when on-console.

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BIOGRAPHY

Keri Bean received a B.S. and M.S. in Meteorology from Texas A&M University in 2010 and 2013, respectively. She has been with JPL for over 7 years. She has worked in operations for the Mars Exploration Rovers, Mars Science Laboratory, and Dawn. She also was the training lead for Mars 2020 and worked in development for NEAScout and Psyche. She is currently a Deputy Rover Planner Lead on MSL and a Helicopter Integration Engineer for Mars 2020.

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Nagin Cox has held leadership and system engineering positions on interplanetary robotic missions including the Galileo mission to Jupiter, the Mars Exploration Rovers, the Kepler exoplanet hunter, InSight, the Mars Curiosity Rover and now the 2020 Perseverance Rover. Nagin is honored to be the namesake for Asteroid 14061. She has also received the NASA Exceptional Service Medal and two NASA Exceptional Achievement Medals. Before her time at JPL, she served in the US Air Force including duty as a Space Operations Officer at NORAD/US Space Command. Nagin holds engineering degrees from Cornell University and the Air Force Institute of Technology as well as a psychology degree from Cornell.

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