MARS 2020 ONBOARD PLANNER - UPDATE AND PREPARATIONS FOR OPERATIONS

Rebekah Siegfriedt[1], Steve Chien[1], Dan Gaines[1], Stephen Kuhn[1], James Hazelrig[1], James Biehl[1], Andrea Connell[1], Raymond Francis[1], and Nick Waldram[1]

[1]*Jet Propulsion Laboratory* California Institute of Technology, USA*

ABSTRACT

The Mars 2020 mission has been developing an onboard planner (OBP) capability to enable the Perseverance rover to operate more efficiently. OBP enables the rover to reschedule activities in response to changes in environmental conditions (such as Mars being warmer than expected, or rover energy/State of charge being higher than expected) as well as execution variations (e.g. activities taking longer or shorter than expected or failing).

In this paper we describe the status of development of this capability including: testing and validation of the flight software, onboard commissioning, ground software to accommodate changing operations, operational readiness tests and training activities. Currently the M2020 onboard planner is scheduled to begin primary operations in October 2023.

Key words: Artificial Intelligence, Space Applications, rovers, robotics, flight software, space mission operations, surface space mission operations.

1. INTRODUCTION

The Mars 2020 mission has been developing an onboard planner (OBP) to improve rover operations efficiency [1]. OBP will allow the rover to respond to unexpected events. For example, if it is warmer than expected rover heating can be reduced. If an activity takes shorter than expected, subsequent activities can execute earlier and the rover can go to sleep and save energy. If an activity takes longer than expected, later activities can be delayed in some cases. Finally, if a drive is going better than expected (e.g. faster) it may be possible to extend the drive to get further along the desired path. All of these can improve rover productivity. The OBP is the flight element, but significant ground software is also required to best operate the rover - Simple Planner (SP) refers to the entire system of flight system, ground system, and operations concept.

Because of the complexity of rover operations and the need to protect the unique resource of the rover, a thorough and deliberate campaign of tests and training exercises is being performed in the leadup to onboard planner use in primary rover operations (currently projected for October 2023).

1. A series of six “tabletop” exercised the ground tools and helped to train the ground operations staff to the new operations workflow.
2. A set of thread tests were executed in which onboard plans were generated and executed on Optimism/VSTB, the hardware test rover operating in the JPL Marsyard.
3. An operations readiness test (ORT) was executed in August 2023 to further exercise both the software and processes for operations of SP.
4. A series of three commissioning activities were performed onboard the Perseverance rover on Mars to exercise the OBP flight software and confirm that the software is operating as expected.
5. A Simple Planner flight school was developed and over 150 of the M2020 team were trained in the new software and operations processes related to SP.

All of these efforts will culminate with the operational rollout of SP with a scheduled date of October 2023 for the first version called SP1 which focuses on resource savings (energy) for future sols. This will be followed by a second tranche of capabilities in the SP2 delivery scheduled for operations in May 2024 which will enable use of saved resources (time, energy) within the same sol.

SP is part of a set of autonomy capabilities onboard the Perseverance rover [2] along with enhanced autonomous driving and the AEGIS autonomous targeting software [3].

2. FLIGHT SOFTWARE

The primary component of the Simple Planner (SP) is the OBP which is flight software onboard the Perseverance rover consisting of two main components:

PLAN which is responsible for scheduling activities and PLANC which is responsible for executing the current schedule as well as invoking PLAN when a new plan is needed.

The OBP flight software had to be carefully designed to overcome several challenges of the M2020 mission.

First, the onboard computer for the Perseverance rover is very limited in its computational power. The Rad 750 [4] used in Perseverance only produces 200 MIPS and the OBP only gets a fraction of the entire computing resource [5]. Therefore the PLAN and PLANC modules needed to be carefully designed to fit within limited computation and designed to operate within a carefully prescribed software priority. If rescheduling via PLAN takes too long, much of the benefit of rescheduling is lost. But if rescheduling occurs too often, valuable computer cycles can starve other important tasks onboard the rover. In order to address these tradeoffs, OBP uses a lighter weight *Flexible Execution* and event driven rescheduling [6] to control OBP CPU usage. In addition, a throttling mechanism [5] prevents the OBP from invoking too much so that it starves other software processes.

Second, OBP must address complex thermal management for the Perseverance rover [5]. Many mechanisms onboard the Perseverance rover must be at a safe temperature before being used (such as to drive motors, arm motors, or instruments). Therefore OBP needs to schedule preheat and maintenance heating to support these activities. However the atmospheric temperature varies considerably during the Martian day. So the amount of time to preheat a mechanism to be used depends on the time of day of the usage. In some cases (near mid day and Martian summer) no heating may be required. Alternatively, at some times and seasons, the rover heaters may not be sufficient to maintain operating temperatures. The OBP is responsible for scheduling preheat and maintenance activities to support relevant activities.

Third, OBP must manage rover energy constraints [7]. The Perseverance rover is so energy constrained that merely the rover being awake pushes it into a power negative state. Most activities require that the rover be awake in order to be performed. Therefore a common pattern of operations is that the rover takes naps throughout the martian day, or sol, in order to conserve energy. In addition to scheduling the desired science and engineering activities, OBP must manage the wake sleep schedule of the rover, to conserve energy to enable productive rover science.

2.1. Validation and Testing of the Onboard Planner Flight Software

As a significant flight software capability, OBP requires an extensive validation and testing effort to ensure that the software will perform as intended. OBP validation and verification has followed the same pattern as other JPL autonomy flight software [8]. As such, OBP Validation and Verification [9] uses formal methods, informal methods, and testing focused in a requirements and capability driven fashion.

Specifically, because the OBP is going into operations after Perseverance has already operated for over 2 Earth years (1 Martian Year) on Mars, the OBP team is able to use actual sols of operations adapted to OBP as test cases to both verify correct OBP behavior and also to estimate performance gains from OBP usage. This is a tremendous advantage and effort savings over validation and verification conducted entirely pre operations.

2.2. Commissioning Activities

In order to exercise the OBP flight software capability in the actual rover execution environment, one pre-test and three commissioning activities were run onboard the Perseverance rover to exercise the core OBP capabilities.

In May 2023 as a pre-checkout activity, an onboard test was conducted to verify that OBP parameters could be updated as expected.

Later in May 2023, the Mars 2020 mission successfully completed a first test use of the OBP on Mars. This first stage demonstrated OBP's core activity scheduling and execution behaviors, including reacting to actual activity execution durations. In accordance with the test nature of this activity, all OBP activities had null sequences so that while OBP activities were scheduled, rescheduled, and executed (including adjustments from Flexible Execution), no FSW actions were taken to implement these activities.

In late June 2023, the second OBP commissioning activity was performed. This activity was designed to test OBP's management of heating and rover sleep cycles. For this 2nd activity, if was advance planned in Campaign Implementation 23 June 2023 and Tactical planned 27 June 2023. The test executed 29-30 June 2023. This second commissioning activity tested the onboard planner flight software heating/thermal management and wake-sleep-energy management capabilities. This second activity did actually control the thermal activities for several zones onboard the rover. This second commissioning effort covered a partial sol (martian day).

In late July 2023, a successful 3rd commissioning activity executed on Sol 869. In this activity the OBP for the first time executed science activities including Mastcam-Z, NAVCAM, and MEDA as well as a Heli Comm activity. Although there was an autonav drive fault this did not affect the successful OBP commissioning activity. Successful execution was verified in the downlink portion of the operations shift 1 August 2023. This third activity corresponded to a full sol of typical on Mars activity. While OBP did operate Perseverance in this 3rd commissioning activity, this does NOT represent OBP operational usage.

3. GROUND SOFTWARE

Full utilization of the M2020 OBP requires significant ground operations software. Since the Perseverance rover completed its commissioning activities after landing in Summer 2021, the operations team has been using the Copilot [10] ground-based scheduling system to assist with preheat and wake-sleep scheduling for Perseverance operations along with the Crosscheck [11] system to explain Copilot scheduling as well as schedule constraints restricting when activities can be scheduled. However, in this paradigm, the operations team still operated by specifying ”grounded” activities, e.g. scheduling activities at specific times as chosen by the operations team. More recently, since August 2023, the operations team has been working *constraint-based planning* where constraints are specified and the Copilot scheduler attempts to find times for activities.

However, Copilot and Crosscheck are just a small part of the overall ground software used in the uplink planning process [12]. Both Copilot and Crosscheck work with the primary planning tool - Component-based Campaign Planning, Implementation and Tactical tool (COCPIT).

4. PREPARATION FOR SP GROUND OPERATIONS

The ground operations flow for SP was developed based on considerable surface operations experience in the SP team. In extending and adapting this operations process to the larger M2020 team, a series of outreach efforts as well as operational exercises were executed.

February - May 2023, the SP team held weekly meetings with the Instrument Operations and Science teams to develop strategies for achieving instrument science best utilizing new SP capabilities. Through this continuing sequence of meetings, concepts of operations were developed for each instrument for the varied types of science.

Starting in 2022, the SP team held a series of six Table Top exercises in which an uplink operations team would develop a plan for OBP similar to a Tactical planning cycle using one or more scenarios patterned on an actual sol type. Working through these exercises drove out challenges in operations as well as the ground software capabilities. Each of these Table Tops had a different emphasis as described below.

- OBP Plans and sequencing - focused on how sequences from instruments and rover planners (drive and arm activities) would change in SP operations compared to conventional Master submaster (MSM) operations mode sequences.
- Sampling - focus on how OBP mode would support sols in which samples are collected.
- Mode transition - focus on how planning would handle transitions from OBP mode to MSM mode and vice versa.
- SP breadth - covered tactical planning process for three different sol types
- SP Plan Size Stress test - covered Campaign Implementation (lookahead planning) and tactical operations for a 3 sol plan, the longest likely to occur in operations.
- Team interaction - covered how the PILOT (overall science planner managing the plan in the COCPIT tool) and payload uplink leads (PUL) representing the different instrument teams) should best coordinate.

Additionally, the SP team conducted two Super Thread Tests (TT) which focus on closing the entire loop below:

1. uplink planning,
2. execution on the VSTB using OBP - the Perseverance Rovers Twin testbed at the JPL Marsyard,
3. generation of downlink products,
4. assessment of the rover, and
5. feeding into the next planning cycle.

The TT’s performed are described below.

- Super TT-20 (12-14 July 2023) focused on remote sensing and included uplink planning, VSTB execution of the generated planfile, and downlink. Super TT-20 had limited strategic or lookahead plan development, and was constrained in the types of activities included.
- Super TT-22 (14-17 November 2022) focused on including a more complete operations cycle as well as more rover activities. Super TT-22 included Campaign Implementation (lookahead planning), tactical uplink planning, VSTB execution of planfile, downlink assessment, second uplink planning session. The plan included remote sensing as well as an autonav drive. TT-22 was a more flight-like exercise of uplink and downlink tooling and involved product generation and delivery, SSIM simulation, targeting in ASTRO for robotic activities.

The M2020 Project also conducted a Simple Planner Flight School for training M2020 operations staff in constraint-based planning and changes to the operations flow to best leverage Simple Planner capabilities. The flight school is a seven (7) session set of courses that was taught live and also recorded for staff who could not attend live and for future new staff. In its entirety the Simple Planner Flight School consists of over 10 hours of training and includes the topics as listed below.

Figure 1. OBP generated plan executing on VSTB in Marsyard 15 November 2022 as part of Super Thread Test 22 (Super TT 22).

1. Simple Planner Foundations
2. Science Operations and Instrument Operations Overview
3. Campaign Implementation
4. Simple Planner Planning
5. Tactical Uplink
6. Tactical Downlink
7. Anomalies

In total, as of September 2023, 155 staff have completed some portion of the M2020 Simple Planner Flight School either live July 2023 or using the recorded material. Critically, the recorded material provides reference training material for future mission staffing.

The most comprehensive exercise conducted was the M2020 SP Operational Readiness Test which occurred from 2-15 August 2023. This exercise performed two lookahead planning (Campaign Implementation) shifts, two Tactical planning shifts, and two downlink assessments. Included in these was planning for a 3 sol plan. A VSTB Robotic Arm anomaly prevented VSTB execution of arm motions or drives. This exercise included uplink, downlink, and testbed staff covering both science and engineering encompassing over 100 staff including observers.

5. REMAINING SCHEDULE FOR OPERATIONAL ROLLOUT

As this article goes to press for ASTRA 2023, the current plan is for the SP to begin primary use of SP1 capability in M2020 operations in October 2023. As Fiscal Year 2024 begins in October 2023, additional work is planned to refine operational processes, augment the ground software, and validate and verify SP2 capabilities for scheduled rollout in the May-July 2024 timeframe.

There are also a number of ground planning capabilities identified for improvement in FY24. First, feedback from use of the Crosscheck explanation system [11] has generated new capability requests. Second, a limited execution simulation capability was designed for Copilot but is not ready for operations, extensions of this approach [13] from Monte Carlo to Importance Sampling to increase efficiency and give the operations team feedback on what range of executions are likely to occur is highly desirable. Additionally, visualization of potential outcomes [14] is a key part of any such process.

6. RELATED WORK

Flight of onboard planners/schedulers onboard spacecraft and rovers is exceptionally rare and is unprecedented for a flagship class mission like M2020.

In 1999, the Remote Agent flew the RAX-PS planner which controlled the Deep Space One mission for two periods totalling approximately 48 hours [15]. In 2013, the CASPER planner flew onboard the IPEX cubesat [16] for over 1 year. More recently, the Mexec planner (related to the M2020 OBP [17]) flew onboard the ASTERIA cubesat for 4-20 September 2019 [18]. Finally, the CASPER planner flew onboard the Earth Observing One mission from 2004-2017, controlling all EO-1 activities for over a dozen years [19]. All of these prior flights were relatively simple missions and do not compare to the extremely complex M2020 - Perseverance mission.

It is worth noting that several lunar rover missions with significant autonomy are scheduled for launch in the near future.

- The Moonranger [20] mission will hunt for lunar ice autonomously.
- The CADRE mission [21] will use the Mexec planner to coordinate measurements on the lunar surface.
- The VIPER rover [22] will autonomously map and hunt for lunar ice

7. CONCLUSIONS

The Mars 2020 mission is in the process of deploying a significant onboard autonomy capability - the Simple Planner (SP). SP includes the OBP flight software that enables the rover to adjust activities to unexpected conditions (such as ambient temperature warmer than expected or battery state of charge being higher than expected) as well as execution variations (activities failing, or taking longer or shorter than projected).

Because of the complexity of rover operations, deploying such a capability requires: extensive testing of operational workflows, flight software, and ground software as well as operations training. We describe these activities in preparation for SP rollout with first operations currently scheduled for October 2023.

ACKNOWLEDGMENTS

The research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not constitute or imply its endorsement by the United States Government or the Jet Propulsion Laboratory, California Institute of Technology.

This work was sponsored by the Mars 2020 Mission, the JPL Director's Innovation Fund, and the JPL Resarch and Technology Development Program.

REFERENCES

[1] Dan Gaines, Steve Chien, Gregg Rabideau, Stephen Kuhn, Vincent Wong, Amruta Yelamanchili, Shannon Towey, Jagriti Agrawal, Wayne Chi, Andrea Connell, Evan Davis, and Colette Lohr. Onboard planning for the mars 2020 perseverance rover. In *16th Symposium on Advanced Space Technologies in Robotics and Automation*, June 2022. URL `https://ai.jpl.nasa.gov/public/documents/papers/M2020-OBP-ASTRA-2022-Final.pdf`.

[2] Vandi Verma, Mark W Maimone, Daniel M Gaines, Raymond Francis, Tara A Estlin, Stephen R Kuhn, Gregg R Rabideau, Steve A Chien, Michael M McHenry, Evan J Graser, et al. Autonomous robotics is driving perseverance rover's progress on mars. *Science Robotics*, 8(80):eadi3099, 2023.

[3] R. Francis, T. Estlin, G. Doran, S. Johnstone, D. Gaines, V. Verma, M. Burl, J. Frydenvang, S. Montao, R. C. Wiens, S. Schaffer, O. Gasnault, L. DeFlores, D. Blaney, and B. Bornstein. Aegis autonomous targeting for chemcam on mars science laboratory: Deployment and results of initial science team use. *Science Robotics*, June 2017.

[4] Rad750. `https://en.wikipedia.org/wiki/RAD750`.

[5] D. Gaines, G. Rabideau, V. Wong, S. Kuhn, E. Fosse, and S. Chien. The mars 2020 on-board planner: Balancing performance and computational constraints. In *Flight Software Workshop*, February 2022. URL `https://ai.jpl.nasa.gov/public/documents/presentations/OBP-FSW22-2022-01-07.pdf`.

[6] J. Agrawal, W. Chi, S. A. Chien, G. Rabideau, D. Gaines, and S. Kuhn. Analyzing the effectiveness of rescheduling and flexible execution methods to address uncertainty in execution duration for a planetary rover. *Robotics and Autonomous Systems*, 140 (2021) 103758, 2021. URL `https://doi.org/10.1016/j.robot.2021.103758`.

[7] W. Chi, S.Chien, and J. Agrawal. Scheduling with complex consumptive resources for a planetary rover. In *International Conference on Automated Planning and Scheduling (ICAPS 2020)*, Nancy, France, October 2020. URL `https://ai.jpl.nasa.gov/public/papers/chi-icaps2020-wakesleep.pdf`.

[8] Steve Chien. Formal methods for trusted space autonomy, boon or bane? In *NASA Formal Methods Symposium*, May 2022. URL `https://ai.jpl.nasa.gov/public/documents/papers/chien-nfm-2022.pdf`.

[9] S. Parjan and D. Gaines. Towards trusted mars autonomy: V and v of the m2020 on board plannerâs thermal management capabilities. In *Proceedings of the International Workshop on Planning and Scheduling for Space (IWPSS)*, July 2023. URL `https://ai.jpl.nasa.gov/public/documents/papers/parjan-m2020-iwpss-2023.pdf`.

[10] A. Yelamanchili, J. Agrawal, S. Chien, J. Biehl, A. Connell, U. Guduri, J. Hazelrig, I. Ip, K. Maxwell, K. Steadman, and S. Towey. Ground-based automated scheduling for operations of the mars 2020 rover mission. In *Proceedings Space Operations 2021*, May 2021. URL `https://spaceops.iafastro.directory/a/proceedings/SpaceOps-2021/SpaceOps-2021/6/manuscripts/SpaceOps-2021,6,x1385.pdf`.

[11] J. Agrawal, A. Yelamanchili, and S. Chien. Using explainable scheduling for the mars 2020 rover mission. In *Workshop on Explainable AI Planning (XAIP), International Conference on Automated Planning and Scheduling (ICAPS XAIP)*, October 2020. URL `https://arxiv.org/pdf/2011.08733.pdf`.

[12] Andrea Connell and Matthew Hurst. Ground software to support autonomous onboard scheduling for mars perseverance rover. In *2023 IEEE Aerospace Conference*. IEEE, 2023.

[13] W. Chi, J. Agrawal, S. Chien, E. Fosse, and U. Guduri. Optimizing parameters for uncertain execution and rescheduling robustness. In *International Conference on Automated Planning and Scheduling (ICAPS 2019)*, Berkeley, California, USA, July 2019. URL `https://ai.jpl.nasa.gov/public/papers/chi-icaps2019-optimizing.pdf`.

[14] Basak Alper Ramaswamy, Jagriti Agrawal, Wayne Chi, So Young Kim, Scott Davidoff, and Steve Chien. Supporting automation in spacecraft activity planning with simulation and visualization. In *Proceedings of Science and Technology Forum and Exposition*. AIAA, 2019. URL https://ai.jpl.nasa.gov/public/papers/basak-aiaa2019-supporting.pdf.

[15] Ari K Jónsson, Paul H Morris, Nicola Muscettola, Kanna Rajan, and Benjamin D Smith. Planning in interplanetary space: Theory and practice. In *Proceeding of Conference on Artificial Intelligence Planning Scheduling*, pages 177–186, 2000.

[16] S. Chien, J. Doubleday, D. R. Thompson, K. Wagstaff, J. Bellardo, C. Francis, E. Baumgarten, A. Williams, E. Yee, E. Stanton, and J. Piug-Suari. Onboard autonomy on the intelligent payload experiment (ipex) cubesat mission. *Journal of Aerospace Information Systems (JAIS)*, April 2016.

[17] Multimission scheduler and Executive - MEXEC. https://ai.jpl.nasa.gov/public/projects/mexec/.

[18] M. Troesch, F. Mirza, K. Hughes, A. Rothstein-Dowden, R. Bocchino, A. Donner, M. Feather, B. Smith, L. Fesq, B. Barker, and B. Campuzano. Mexec: An onboard integrated planning and execution approach for spacecraft commanding. In *Workshop on Integrated Execution (IntEx) / Goal Reasoning (GR), International Conference on Automated Planning and Scheduling (ICAPS IntEx/GP 2020)*, October 2020. URL https://ai.jpl.nasa.gov/public/papers/IntEx-2020-MEXEC.pdf.

[19] S. Chien, R. Sherwood, D. Tran, B. Cichy, G. Rabideau, R. Castano, A. Davies, D. Mandl, S. Frye, B. Trout, S. Shulman, and D. Boyer. Using autonomy flight software to improve science return on earth observing one. *Journal of Aerospace Computing, Information, and Communication (JACIC)*, pages 196–216, April 2005. URL https://ai.jpl.nasa.gov/public/papers/chien-JACIC2005-UsingAutonomy.pdf.

[20] Moonranger. https://labs.ri.cmu.edu/moonranger/, 2023.

[21] Cooperative Autonomous Distributed Robotic Exploration (CADRE). https://ai.jpl.nasa.gov/public/projects/cadre/, 2023.

[22] T. Fong. VIPER – Volatiles Investigating Polar Exploration Rover. https://ntrs.nasa.gov/api/citations/20210012662/downloads/viper-2021-03-29.pdf, 2021.