From Prime to Extended Mission: Evolution of the MER Tactical Uplink Process

Andrew Mishkin[*] and Sharon Laubach[ε]
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA

To support a 90-day surface mission for two robotic rovers, the Mars Exploration Rover mission designed and implemented an intensive tactical operations process, enabling daily commanding of each rover. Using a combination of new processes, custom software tools, a Mars-time staffing schedule, and seven-day-a-week operations, the MER team was able to compress the traditional weeks-long command-turnaround for a deep space robotic mission to about 18 hours. However, there was never an intention of maintaining the pace of this process indefinitely. Even before the end of the three-month prime mission, MER operations began evolving towards greater sustainability. A combination of continued software tool development, increasing team experience, and availability of reusable sequences first reduced the mean process duration to approximately 11 hours. The number of workshifts required to perform the process dropped, and the team returned to a modified "Earth-time" schedule. Additional process and tool adaptation eventually provided the option of planning multiple Martian days of activity within a single workshift, making 5-day-a-week operations possible. The vast majority of the science team returned to their home institutions, continuing to participate fully in the tactical operations process remotely. MER has continued to operate for over two Earth-years as many of its key personnel have moved on to other projects, the operations team and budget have shrunk, and the rovers have begun to exhibit symptoms of aging.

Nomenclature

APAM = Activity Plan Approval Meeting
CoUGAR = Command and Uplink Generation and Review
ERT = Earth Receive Time
ETT = Earth Transmit Time
IST = Integrated Sequencing Team
MER = Mars Exploration Rover
MGS = Mars Global Surveyor
RSVP = Rover Sequencing and Visualization Program
SAP = Science Activity Planner
sol = Martian solar day
SOWG = Science Operations Working Group
SRET = Spacecraft Rover Engineering Team

I. Introduction

THE Mars Exploration Rover (MER) mission successfully landed two mobile geological laboratories on the Red Planet in early 2004. As originally envisioned, MER was intended to operate the two robotic rovers—named "Spirit" and "Opportunity"—on the surface of Mars for approximately 90 Martian days (or "sols") each. The rovers' lifetime was assumed to be limited due to expected buildup of dust on the solar arrays, which in turn would reduce the energy available for rover science activities and traverse. This constraint resulted in the design of an

[*] Principal Engineer, Planning and Execution Systems Section, MS 301-250D
[ε] MER Integrated Sequencing Team Chief, Planning & Execution Systems Section, MS 264-422

intense tactical operations process capable of achieving the defined mission objectives within the presumed short mission duration. Due to the inherent non-determinism in the execution of rover traverse and instrument placement in the poorly modeled planetary surface environment, and distinct from most robotic deep space missions, MER surface operations needed to be reactive, with the plan for each sol responding to the results achieved on the prior sol. For the MER prime mission, these requirements led to a seven-day-a-week multi-shift 18-hour command-turnaround process slaved to the Mars local time at each landing site, which planned one sol's worth of rover activities during each planning cycle. The two operations teams, one for each rover, literally lived on Mars-time, with each team in a different Martian time zone.

As the MER surface mission unfolded, it became clear that the rovers were likely to survive and remain functional for far longer than originally anticipated. The operations process in place would require modification to enable sustained operations over an indefinite period, while reducing overall operations team size and lowering operations costs. Process and software tool re-design eventually reduced the duration of the tactical operations process to 8 to 10 hours, which has enabled a single-shift planning cycle and consolidation of several team positions for the current extended mission. We describe the evolution of the tactical process to its current form, as well as the logistical challenges of working on a 5-day-a-week Earth-time schedule, including planning up to 3 rover sols of activity during one operations team work shift. For example, due to Earth-time/Mars-time phasing, uplink planning for the next sol must sometimes proceed before the current sol's activities have completed. In such cases, the team must plan in "restricted" mode, such that rover driving or instrument arm placement is permitted only every other sol, to provide the opportunity for the success of rover motion activities to be assessed prior to planning the next motion. As of this writing, the MER extended mission continues, with both rovers conducting science observations on a daily basis, operated by a team of scientists and engineers one-third the size of the operations team present during prime mission.

II. Drivers and Attributes of the Original MER Operations Design

A. Limited Lifetime

During the development of the MER project, the lifetimes of the two rovers were expected to be short. The "warranty" (i.e., the mission lifetime requirement) for the rovers was specified as 90 sols, or 90 Martian days. Assuming successful landings, energy models indicated that the rovers would survive as long as 140 sols or so. Data gathered during the Mars Pathfinder mission's 83 sols in 1997 had shown a dust buildup on the solar arrays of about 0.2% per sol. A combination of this dust settling and the changing Martian seasons (particularly for Spirit, located further from the equator) would in time leave the rovers with too little energy for traverse, and eventually not even enough for overnight survival heating. Some forecasts indicated that the effect of the dust would be so pronounced that the rovers would be capable of achieving more in the first 30 sols of the surface mission than in the remaining 60 sols. This lifetime constraint put a premium on every command opportunity.

B. Reactive Operations

For most robotic deep space missions, a single command load may be prepared weeks or months in advance of use, and govern the actions of the target spacecraft for a like period of time (and often, sequence preparation time exceeds on-board execution time). For a planetary surface mission in which rover traverses and otherwise interacts with the terrain, there may be more relative uncertainty in the vehicle's position after an attempted drive of 3 meters than in a free-flying spacecraft's position after a million kilometers of travel through space. A rover may slip while driving across the surface, or hit a buried rock and make no further progress. The Spirit and Opportunity rovers are capable of autonomous hazard detection and avoidance; they may reach the desired target location, but due to the need to avoid a hazard unseen by ground operators, may take longer to reach that location, and may reach the target facing an a priori unknown heading. And the choice of what target to approach next, and the determination of where it is safe to drive or to deploy the instrument arm, depend on the images from the latest rover position. All of these factors force the operations team into a reactive mode: to plan what a rover should do next, the results of what the rover just attempted must be known.

C. Limited Communications Opportunities and Downlink Bandwidth

The solar-powered rovers would not have the energy to transmit continuously through their X-band direct-to-Earth links, and would also be limited by heating of the transmitter over time. Although UHF relay through the MGS and Mars Odyssey orbiters was incorporated into the mission design, these links had yet to be proven, and were presumed to have long latencies. Therefore, the mission developed the concept of "critical" data, defined as that data required to support the next planning cycle. Critical data must fit into the X-band session, while most science data not needed for operations planning would be relegated to the UHF relay links. The capacity of the X-band link would be about 20Mbits per sol.

Additionally, two factors limit the number of opportunities to transmit commands to the rovers: again, lack of energy to keep the high gain X-band receiver powered continuously, and the need to negotiate use of the Deep Space Network with all other deep space projects, including other spacecraft at Mars (such as the other rover).

D. Time Delay

With roundtrip communications time delays between Earth and Mars of 6 to 40 minutes, depending on relative orbital position, direct teleoperation or "joysticking" of the rovers would not be feasible. This constraint drives the use of stored command sequences for controlling the rovers, and the requirement for the rovers to be capable of autonomous surface navigation and hazard avoidance.

E. Every-Sol Commanding

Given the presumed limited surface lifetime and non-determinism of rover activities, the key to achieving the MER mission objectives was to command the rovers as often as reliably possible. For nominal surface operations (after rover deployment from the lander), the selected frequency of commanding was once per Martian sol. In this approach, the rover would downlink its critical data in mid-afternoon each sol, after completing all major traverse or robotic arm activities. The ground would then uplink the next command load the following Martian morning. (As a result, the entire sequence preparation process—from telemetry analysis to final upload product generation, review, and approval—would need to fit into the Martian night.) Since the rover would be largely dormant overnight (except for in-situ instrument integration and UHF relay sessions), the rover state as downlinked in the afternoon would be a good predictor of the state at the time the new command load would be received onboard. Even with every-sol commanding, over 1% of the entire surface mission would be consumed per command cycle.

F. Mars-Time

How does one schedule operations teams to operate spacecraft slaved to another planet's diurnal cycle? The mean length of a Mars day—at about 24 hours and 40 minutes—is frustratingly close to an Earth day. MER chose to put its operations teams on the same schedule as the rovers: Tactical team workshifts started 40 minutes later each day. By kicking off the operations process as soon as the Mars afternoon downlink was received on the ground, the team always had the maximum possible number of workhours available between the downlink and the next uplink. (Early in the mission, virtually all of these workhours were consumed.) Working Mars-time also ensured that shift handovers occurred at the same point in the planning process, avoiding the necessity of cross-training the entire team in multiple roles.

Of course, since the two rovers were to land on opposite sides of the planet, the operations teams for each rover would be living in different Martian time zones.

III. Operations Process for the MER Prime Mission

At the start of the surface mission, the MER operations process was described as the "overnight" tactical timeline, since the process was performed primarily during the Martian night while the rover slept. The process executed according to a strict schedule (see Fig. 1), to ensure that the command load would be ready for uplink before the communications opportunity arrived. The key steps of the tactical process are described below.[1]

A. Receipt of Downlink

After completing its final traverse or instrument placement for the sol, the rover transmits its critical data during a communications session up to about an hour in duration.

B. Engineering Downlink Assessment

As the data is received on the ground, engineering team members immediately begin assessing the health of the rover, determining that no anomaly has occurred and that there are no contraindications to performing a normal planning cycle. Automated tools begin constructing data products from the downlink stream, including images. Calibrated images are due for delivery to the planning process within 30 minutes of the end of the downlink.

C. Science Downlink Assessment and Science Activity Planning

Even before downlink begins, subgroups within the science team begin planning observations and partial activity plans contingent on the successful execution of the current sol's plan. When the downlink arrives, science team members assess the health of the onboard instrument suite, and the veracity of the instrument data products. The team continues activity planning, representing and targeting the activities in the SAP (Science Activity Planner) software tool. Depending on the received downlink, activities may be refined, modified, or thrown out and replaced. At 1800 Mars local time, the Science Operations Working Group (SOWG) meeting is convened. At the start of this meeting, a representative of the engineering team presents the status of the rover, and re-confirms the resources available for the next sol. Subsequently, proposed activities from the several subgroups are merged, rejected, and re-worked. Under the direction of the SOWG Chair, the team prioritizes activities for inclusion in the science plan, and for level of criticality to the next planning cycle. As it is being worked, the preliminary plan is repeatedly modeled for resource usage, including duration, energy, and data volume generated.

Members of the Integrated Sequencing Team (IST) attend the SOWG meeting, and assess the feasibility of the preliminary science activity plan from two perspectives: 1) will the rover be capable of executing the plan on Mars, and 2) will the operations team have time to transform the proposed plan into a complete, validated command load in time for the Mars morning uplink opportunity. Among other evaluators, the Rover Planner engineer assesses the feasibility and safety of any traverses or instrument/robotic arm placement required to reach science targets requested by the science team.

The SOWG meeting must deliver the file defining the preliminary science activity plan for the sol by 2000 Mars local time. The bulk of the science team is released from the tactical process at this point.

D. Activity Plan Refinement and Validation

The center of activity now shifts to the sequencing room, where the members of the IST and of the Spacecraft Rover Engineering Team (SRET), instrument sequencing experts from the science team, and the SOWG Chair continue developing the rover command load for the sol. The team integrates engineering activities into the preliminary plan, formally schedules all activities, and models the plan in detail for resource consumption. Activities that do not fit within the available resources will be deleted from the plan. The SOWG chair represents the overall science team for any such intra-science decisions, guided by the established activity priorities; this approach allows for on-the-spot resolution of conflicts to keep the time-constrained process on track. The activity planner must produce a conflict-free plan within the available rover resources in time for the scheduled review meeting. Higher priority activities are scheduled first, so that if time runs out, only the lowest priority items will have been lost.

While the overall activity plan is in work, the Rover Planner uses the Rover Sequencing and Visualization Program (RSVP) to design and simulate all rover traverse and robotic arm activities. RSVP fully represents the 3-dimensional terrain model derived from the stereo imagery returned from the rover. Due to the fidelity required to plan rover and arm motion activities, this part of the planning process is equivalent to developing a draft version of the rover motion command sequences.

E. Activity Plan Review

At 2345 Mars local time, the Activity Plan Approval Meeting (APAM) is convened. The team reviews both the overall activity plan and the rover motion plan. All documents and visual simulations of rover motion are projected from appropriate team member workstations, so that the entire co-located team can review them together. The team confirms that resources are within allocations, that activity-level flight rules have been satisfied, and that despite any changes the plan remains consistent with the original intent of the science team. Only very minor changes to the activity plan are permitted at the APAM, such as insertion of opportunistic remote science observations that will not impact onboard resources.

The APAM also serves as a shift handover for many team members. Team members coming on-shift carefully study the final activity plan, and ask questions during the review. After the meeting, incoming and outgoing team members in corresponding roles may confer one-on-one to ensure that the new team member has the situational awareness to take over.

Since there is no further data volume resource modeling after the APAM, it is crucial that no changes that would significantly affect this resource are introduced post-APAM.

F. Command Sequence Generation

As soon as the SOWG meeting ends, the instrument sequencing experts begin designing the command sequences to implement all instrument activities. Using RSVP, they work in parallel with the activity validation and rover motion planning tasks, to ensure that the sequences will be ready in time. However, until the activity plan has been approved, there is the risk that a given activity will be deleted from the plan, and therefore that any sequence built to execute that activity may never be used. This risk of wasted effort is small compared to the time saved by not waiting for the final activity plan to be delivered. Thus, sequencing begins well before the APAM, and continues for two hours after the APAM.

Following the APAM, a team member produces the “master” and “submaster” command sequences, which together embody the activity plan structure in the form of commands. These sequences command rover wakeups and shutdowns, and determine when each of the individual instrument activity sequences will kick off.

G. Sequence Integration and Validation

At 0200, the team reviews the master, submaster, and robotic motion sequences in detail. Any errors identified are corrected in real-time, and the modifications reviewed again by the team. All sequence developers must deliver their individual validated sequence files by the conclusion of this review.

The Sequence Integration Engineers (SIE) now take on the task of integrating the 30 or more individual sequences into a single command load, producing the command files and review products, and performing both manual and automated cross-sequence flight rule checks on the full sequence set, while other team members conduct a software simulation of uplinking the command load and of the execution of selected sequences. (Due to the lack of available time, MER does not validate every sequence on a testbed before uplink, unlike most other missions. Only first-time critical events are run on a testbed before uplink, and by necessity, these events must be planned and tested ahead of time outside of the tactical process before they can be introduced into a given sol’s plan.)

In addition, the team members manage the sequence library—including the set of on-board sequences—ensuring sufficient capacity for new sequences and managing sequence versions.

H. Command Review

The final review gate is the Command Approval Meeting, at which the team confirms that all validation and flight rule checks have been successfully performed, without discovery of any errors that will impact execution of the command load.

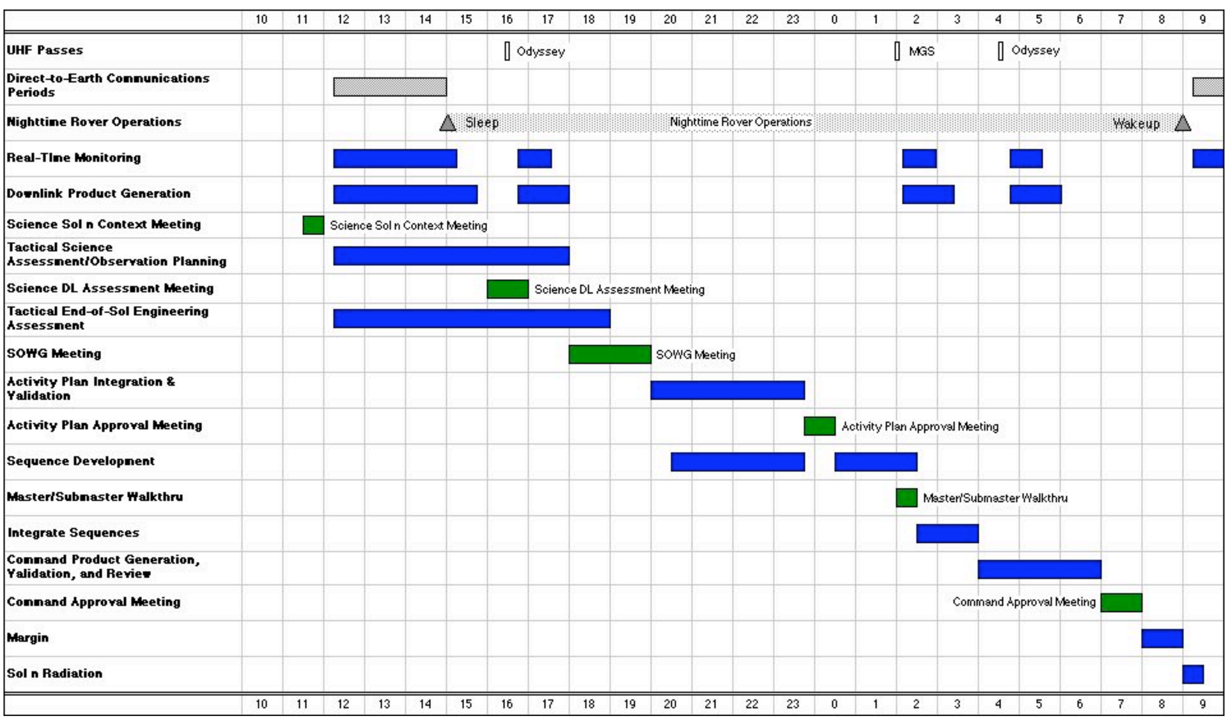

Figure 1. MER Prime Mission “Overnight” Tactical Timeline.
Time scale represents Mars local time at the rover landing site.

I. Transmission of Commands to the Spacecraft

At the Command Approval Meeting, the command forms are approved, together with the instructions specifying the exact order of transmission of the command files and associated real-time commands. These signed documents (which, together with the activity plan approval form, are the only paper documents required by the tactical process), are hand-delivered to the workstation from which the commands will be sent to the proper DSN station and transmitted to the spacecraft. Due to the time delays inherent in Earth-Mars communications, no immediate acknowledgment of command receipt is available from the rover. Instead, the DSN listens for a carrier signal "beep" tone at a specified time determined by commands contained in the new command load, thereby confirming that the new load is running onboard. If the beep is instead received at a second specified time, this will mean that the prior sol's command load is still running, and the new load was not properly received.

IV. Extended Mission 1: Returning to Earth

A. Unsustainability of Mars-Time Operations

During MER's prime mission, the rovers' operations teams worked a 24/7 "Mars-time" schedule, pegged to the solar cycle of each rover's landing site on Mars. (A "sol", or Martian day, is roughly 40 minutes longer than an Earth day.) While this schedule maximized the number of hours available for the tactical process to plan the next sol's activities (beginning immediately after downlinked telemetry was received and allowing margin before command uplink was required), it meant not only that teams would be required to work outside of normal business hours, but also that their Earth-bound shift start times would rotate forward roughly 40 minutes—to match the same "Mars-time" shift start time—each successive day.

Living on Mars-time was no mean feat. It meant that the team would emerge from their shift at the same Mars local time each sol, but the corresponding Earth local time would rotate through the day—so if at the beginning of the prime mission someone's shift began in the early evening, a week later they'd be starting work in the middle of the night, and a week after that, mid-morning. Outside the MER tactical environment, the team had to deal with family, friends, and other tasks which still ran on normal Earth-time schedules, as well as attempt to sleep before they had to return for their next shift. On top of living on Mars-time, the shifts themselves were long and intense. Fatigue, despite countermeasures taken to prevent it, was always a potential issue. Additionally, team members felt increasingly isolated from the world outside MER's tactical environment.

Thus, the key change required for sustainability was moving the team off of Mars-time. Since the main driver for working Mars-time was the number of hours required for turning around a command load, the length of the tactical shift had to be reduced. Automation proved to be the enabling technology, supplemented by the accumulation of reusable instrument command sequences, and streamlining of team member functions as the team learned exactly what was needed. Together, these improvements shortened the tactical process just enough so that margin could be spent to return the team to a modified Earth-time schedule.

B. Modified Earth-Time Schedule

Due to Earth-time/Mars-time phasing, to the length of time required to plan the next sol's activities, and to the fact that the rovers were still a wasting resource, the team could not simply change to a fixed Earth-time shift schedule. Instead, a "modified Earth-time" scheme was devised which would maximize the commandability of the rovers, given the new tactical process duration, but still limit how much a team member's shift could move relative to Earth local time.

Since the rovers' uplink and downlink times were still pinned to Mars local time, those milestones would still rotate through the Earth day. When the time that a rover's downlinked telemetry would be received on Earth ("Earth receive time", or ERT) hits early enough in the Earth day, and the time that the rover's new set of commands needs to be uplinked ("Earth transmit time", or ETT) is late enough, the operations team is able to work during normal business hours (8 AM until 5 PM) to plan the next sol. This period in the schedule is termed "nominal sols". As the rover's downlink ERT shifts later and later, the team's workday on these "slide sols" would start later, until the end of the tactical process hits the latest possible time the scheme would allow (10 PM). At that point, the tactical process on the next day would necessarily begin before the downlinked telemetry had arrived and been analyzed. Since the planning of robotic rover motions requires knowledge of the state of completion of prior commanded robotic motion (including terrain imagery), if the tactical process begins before a rover's downlink ERT, then these types of motions could only be allowed every other sol—in order to allow the telemetry containing the robotic state to be received and analyzed on Earth before planning the next set of robotic motions for that rover. Hence, this period in the modified Earth-time schedule, when the tactical process begins before the prior sol's telemetry had been analyzed, is termed "restricted sols". When the downlink ERT and uplink ETT times again rotate far enough

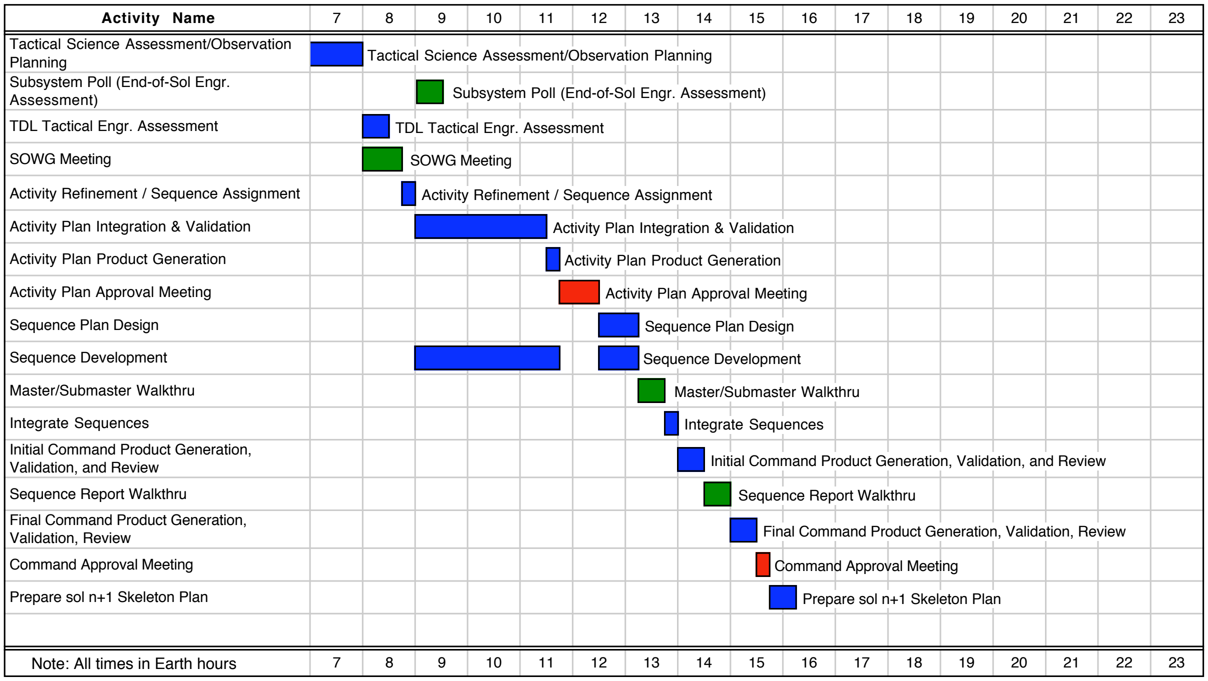

Figure 2. Typical Tactical "Earth-Time" Operations Timeline.
Time scale represents Earth local time at the Jet Propulsion Laboratory.

through the Earth day, the team can start to return to normal, unrestricted planning: first, by inserting a "Skip Day" (also known as a "soliday"), in order to realign the sol being planned on a given day with the sol being uplinked that day. However, at this point, the uplink ETT is still fairly early in the day, so for the next few days the tactical process begins at the earliest time the scheme will allow (7 AM), and the days are called "tight sols". Once the rover's uplink ETT rotates late enough, the schedule resets to normal business hours. This cycle reoccurs every 37 Earth days. (Note that the use of "sol" in this context is a misnomer, which nevertheless has been adopted by the MER team. Strictly speaking, "nominal", "restricted", "slide", and "tight" refer to types of planning days.)

Because Spirit and Opportunity are on opposite sides of the Red Planet, the rovers are in two different martian time zones, roughly 12 martian hours apart. Thus, the modified Earth-time schedules for each rover team are offset from one another such that on any given week, usually one rover or the other is in its "restricted sol" period.

Changes in the process and in plan content had to be made to respond to this new schedule, since the downlinked telemetry could now be received during (or after) the tactical process, forcing a heavy reliance on predicted rover state (including the set of on-board sequences) and accommodation of the risk of variance from that predicted state. For example, if the tactical uplink process on a given day began before the downlink arrived, science activities were chosen which did not depend on successful completion of the prior sol's activities. In addition, since process milestones were no longer pegged to specific Mars times, they were instead tied to projected durations for the intervening steps, to ensure the process completed within the allotted shift duration (see Fig. 2).

C. Evolving Process Automation

The team continued to shorten the tactical process, primarily by augmenting their automation tools. One package which had a drastic effect on process length was the Sequence Integration Engineers' tools, called "CoUGAR tools" (for Command and Uplink Generation and Review). The CoUGAR tools automated the design and generation of the "master/submaster" sequences, integration of the science and engineering sequences, sequence management, and generation of the uplink products and the review products as much as possible. Robustness checks were added, to help reduce the amount of time spent on review and reduce susceptibility to user error. In addition, a method was developed so that the Sequence Integration Engineers could "piggyback" on robotic simulation results already created by other team members, avoiding the time and risk of re-running those simulations (which required highly-specialized training to perform correctly, and required information not readily available to the SIE). Other roles developed tools and templates to automate or otherwise facilitate their tasks: for example, to do rough resource calculations to enable an early "skeleton" sketch of a sol's activity plan; to aid in the development, verification, and validation of the complex robotic motion sequences; to manage and deliver reusable "library" sequences; to generate common custom engineering sequences; and to perform validity and flight rule checks on the sequence set.

The tools to automate portions of the tactical process were developed—and continued to evolve—during surface operations, as tasks amenable to automation were identified, and as new situations were discovered which lent themselves to automated checks. Care needed to be taken to identify and preserve process "gateways": transitions within the tactical process over which human review was required to validate the tools' output, and over which no automation was allowed, since if errors were not detected until the end of the process, there would not be sufficient time to go back and make corrections, resulting in rejection of the plan and a wasted sol.

D. Reduced Command-Level Modelling

Another change was the decision to limit other kinds of modeling done at the command level, instead relying on resource modeling at the activity level to validate the sol's plan. This decision required that no significant changes be made to the plan downstream of the Activity Plan Approval meeting, but further reduced the length of the tactical process.

Overall, these improvements, along with increased reuse of sequences and a better understanding of what activities would fit into a given sol's plan, shortened the tactical process to roughly 8 hours, and allowed some roles to be combined into a single role which now fit into a single shift. The new process duration was re-factored into the modified Earth-time schedule, allowing the schedule to continue to approach normal working hours over the seven-day workweek.

V. Extended Mission 1: Working 5 Days a Week

As it became clear that the rovers were continuing to survive far longer than the 90-sol prime mission, it was also burdensome to the team to continue to work weekends and holidays. The decision was made to allow the team to plan three sols' worth of activities on Fridays, and uplink the resulting 3-sol command load. (For holidays, rather than plan more than 3 sols at a time, several multi-sol plans were created over the days leading up to the holiday to cover the affected time—for example, a 2-sol plan on Thursday and a 3-sol plan on Friday would cover a Monday holiday.) Again, since the results of robotic motions over the weekend could not be known during planning, the weekends were treated as a flavor of "restricted sols".

The CoUGAR tools, designed for every-sol commanding, were significantly revamped to allow robust multi-sol planning without severely impacting the length of the tactical process. To minimize impact on the tools, to attempt to minimize the burden on the team for repetitive tasks, and to allow for ease of recovery in case of anomaly during the execution of multi-sol plans, the new process presents the entire multi-sol plan to the team as a single entity through the sequence integration and sequence management phase (although "behind the scenes", the products for each sol are generated and bookkept separately, and sequences must be delivered to each sol they will be used). During uplink and review product generation, the products are expressly created individually for each sol.

In the end, each additional sol in the plan added only an hour to the tactical process, including time for selection of activities for the additional sols, and generation and review of the multi-sol plan's products at various points in the process. A skeleton staff reviews downlinked telemetry over the weekend, and a small on-call team is designated to respond to anomalies as needed.

Due to this new practice, "tight sols" were disallowed on Fridays, since the tactical process would run longer than usual when planning multiple sols. Instead, the period of "restricted sols" would be extended until the weekend, with the "Skip Day" scheduled over the weekend (see Fig. 3).

As a side note, the practice of planning multiple sols is also often used during the period of restricted sols, where one sol containing robotic motion followed by a sol with no robotic activity are planned at once on a given day, followed by a day off for the team.

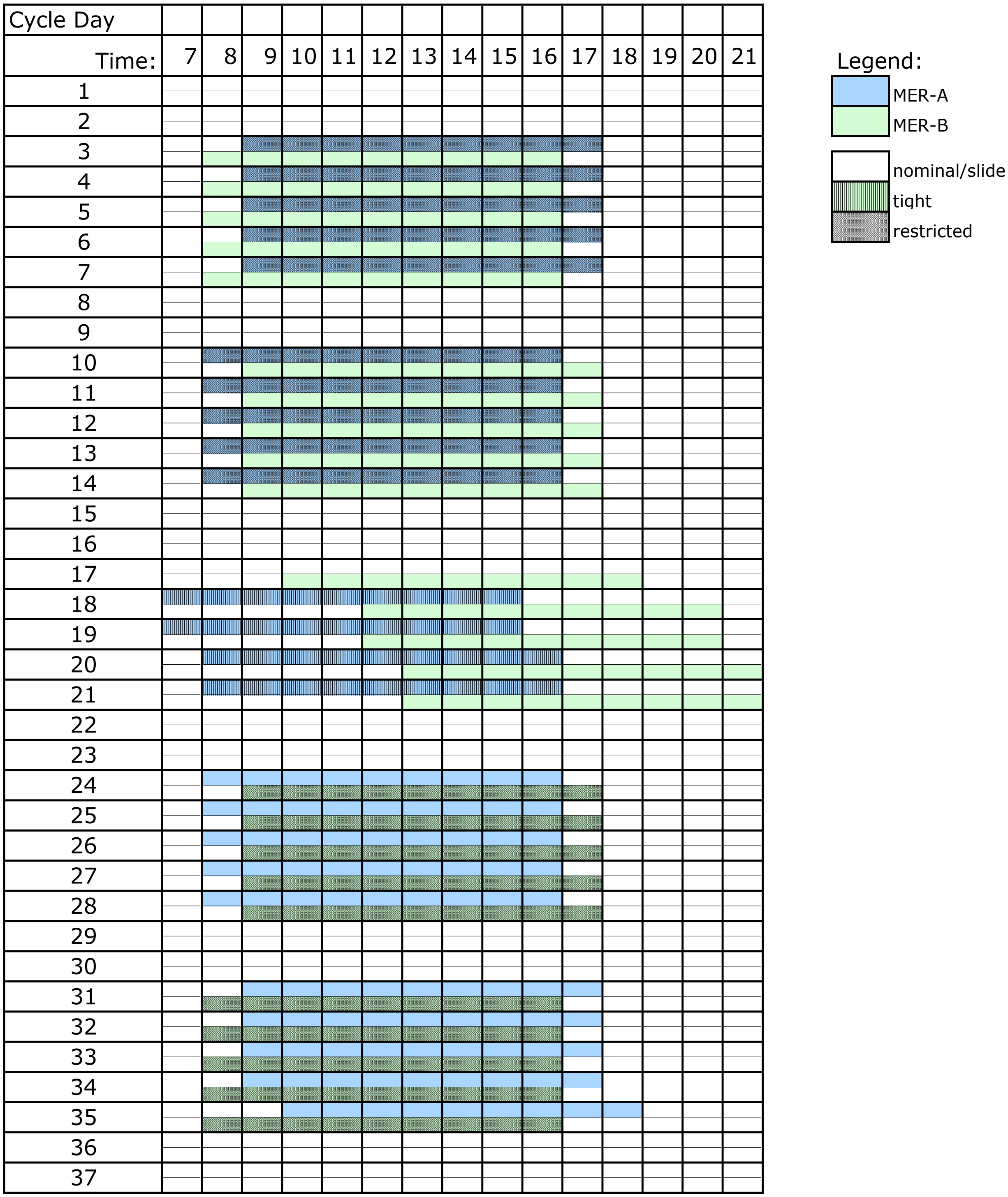

Figure 3. MER Extended Mission Modified Earth-Time Schedule (5 days/week version).
Time scale represents Earth local time at the Jet Propulsion Laboratory.

VI. Extended Mission 2: Distributed Operations

For the second MER extended mission, it was no longer feasible to keep the entire team co-located at JPL. The original operations design's near-independence from paper documentation facilitated the move to distributed operations, but it was unclear at first how well the collaborative tactical environment, so dependent upon interaction between team members, would translate. Initially, some science team members moved back to their home institutions and attended the SOWG meeting remotely. Given the success of this first move, in September 2004, the SOWG Chair experimentally participated entirely remotely, leading the SOWG meeting from another room and being available during the remainder of the tactical process only over the teleconference line. The process was slightly changed to accommodate the remote SOWG Chair; for example, a webcam was set up to broadcast the information projected onto the screen in the sequencing room during review and approval meetings, and selected intermediate products were moved to a remotely-accessible secure area. Again, the experiment was a success, and now the SOWG Chair is nearly always at their home institution. Finally, using the infrastructure prepared for the remote SOWG Chair, the remaining science team members from outside JPL were able to move back home. Workstations configured with key activity planning and sequencing software were installed at selected remote sites, permitting instrument sequencing experts to deliver their sequences or other products remotely.

The rest of the tactical team—including the Mission Manager, and all IST and SRET team members—are still co-located in the SOWG room and sequencing room at JPL.

VII. Extended Mission 3: Sustaining Operations Despite Personnel Turnover

Many of MER's operations team members had been involved in the development of the MER rovers, and had expert knowledge of how the rovers' systems functioned. As MER moved into its third extended mission, a year after the prime mission ended, these experts began moving on to other projects to return to spacecraft development. MER's tactical process shifts, though shortened, could still be intense, and the robustness of the plans and short duration of the tactical process, as well as appropriate response to anomalies, was dependent on expert operators in many of the tactical roles.

In addition to the pull of other projects on MER's experts, the realities of budget limitations forced further reductions in the size of the operations team, straining the operations process even more. As personnel rolled off of the team, "corporate knowledge" about past operations strategies was sometimes lost. Additionally, an unforeseen consequence of the very successful automation effort was that new personnel sometimes did not learn the details of the process "under the hood", so when unusual circumstances arose, they did not always know how to respond…and occasionally, experienced personnel's skills would become rusty from disuse.

Fortunately, many of the automated aspects of the process made it possible for less-experienced personnel to be trained to perform some key roles. Significant training time was still required, including many "shadow" shifts giving on-the-job exposure to the process. Leadership positions on the team were filled from within the team, reducing the training time required. Formal training materials, including documentation and exercises (often web-based), were produced to aid the incorporation of new personnel. (Such materials were not required during prime mission, since all personnel were familiar with the spacecraft and their roles.) Sufficient training before a new person is needed to fill a role, and capturing the knowledge of experienced personnel leaving the project, are still significant challenges.

Another response to the changing skill set of the operations team has been the slow, organic evolution of tactical roles. As the original personnel filling leadership and systems engineering positions left the project, personnel from other roles within the team were trained to fill these positions, and in turn, new personnel were brought in to fill the newly-created holes. As training times were long, the personnel who had moved to new positions would often "help" those who were filling their old positions, and over time, would simply adopt aspects of their old positions, blurring role boundaries and responsibilities. This tendency—while helping to ensure the continued operations of the rovers as new personnel are brought up to speed—had several unfortunate consequences, among which were increased training time required to move on to the next position, since the more "junior" positions lost exposure to those aspects of the process; the loss of some process robustness, as checks-and-balances between roles were lost and as roles originally intended to have a more supervisory or "independent" perspective became bogged down in process details and product deliveries; and uneven distribution of tasks, leading to over-subscription for some team-members and lack of interesting challenges for others. To address this issue as MER moves towards its proposed fourth extended mission, an ongoing effort is re-examining the tactical roles and determining how tasks should be redistributed to meet the project's needs (including a clear set of responsibilities, process robustness, interest for those filling the roles, and maintaining a training "pipeline") given the current and projected skill set.

VIII. Other Evolutions

An additional consequence of the continued operation of the MER rovers is that the content of each planning cycle, rather than becoming simpler, is actually becoming more complex, due to the factors described below. As a result, the length of the tactical shift duration is continually tracked, and changes are incorporated—to the process, the tools, training materials, instructions to the team leads, new interfaces with other spacecraft, or other areas—to keep improving the tactical operations process, to keep the plans and process manageable for the team, and to maximize the science return of our rovers while they continue to amaze us with their longevity.

A. Aging Rovers

As the rovers continue to operate well beyond their original expected lifetime, inevitably components begin to fail. Upon landing, one of the rovers had an arm actuator heater stuck on, necessitating a change to how that rover was operated (including a flight software change), in order to preserve energy for science activities. In addition, over the last nearly 1750 sols of combined rover operations, various robotic actuators have exhibited flaky behavior or have failed outright. In response, the team has devised workarounds and new operation techniques to continue to maximize mobility and science return. These new techniques, however, significantly increase the complexity of both planning and generating the command load.

B. New Flight Software

MER has had two upgrades to its on-board flight software since landing on Mars, with a third planned for the summer of 2006. The new flight software has often incorporated fixes which help to reduce operations complexity in some areas, but also added capabilities, the use of which—while augmenting the rovers' ability to continue operating, to increase traverse capability, and to gather and return more science data—often increased operations complexity beyond the level originally experienced.

C. Changing Martian Seasons

The MER rovers have also now operated through more than an entire Martian year, encountering every Martian season. As of this writing, the MER rovers, both of which are in the southern hemisphere, are experiencing Martian autumn and are rapidly approaching winter. The changing seasons each bring challenges, which the operations strategy must adapt to: during spring and summer, solar energy is increasingly plentiful, but care must be taken so the rovers and their instruments do not overheat. During fall and winter, the sun drops closer to the horizon, significantly decreasing the solar energy available for rover operation, and heaters must be used more often to keep the rovers and their instruments warm enough, taxing the available energy further. In addition, the energy available for communications opportunities varies with the seasons, affecting how much data can be downlinked on a given sol, and therefore how much capacity is left on-board for new data. Further, atmospheric opacity due to suspended dust changes with the seasons, affecting available energy, and the "cleaning events" which occasionally fortuitously remove dust from the solar panels may be tied to particular seasons. Changes are made to the tools and templates, to aid manageable operations with each change in season.

D. Changing Operations Environment at Mars

The longevity of the rovers has meant that they are still operating even as new spacecraft enter orbit or attempt to land at Mars. The challenges of these changes include increased scarcity of communications opportunities with the rovers, and increased coordination of MER operations with the operations teams of other spacecraft, whose tactical processes have longer latencies and are out-of-sync with MER's 5-day-a-week, modified Earth-time schedule. In response to unavailable uplink opportunities, the team has developed two strategies: where possible, the team uses multi-sol plans to make up for sols without uplink opportunities. If the period without uplink is not supportable in this manner, the team developed the capability to command via relay through the Odyssey orbiter—built into the spacecraft during development, but not exercised except as a brief test until the third extended mission, when operations tools and relay coordination processes with the Odyssey operations team were developed to adapt the existing MER tactical process to the requirements of relay commanding.

IX. Conclusion

Even after more than two years of Mars surface exploration, the MER operations design remains in motion. Changing mission resources, new technology experiments, and the challenges of aging hardware continue to drive improvements and adaptations. This operations evolution will likely go on for as long as Spirit and Opportunity survive.

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References

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