Calculation of Operations Efficiency Factors for Mars Surface Missions

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The duration of a mission—and subsequently, the minimum spacecraft lifetime—is a key component in designing the capabilities of a spacecraft during mission formulation. However, determining the duration is not simply a function of how long it will take the spacecraft to execute the activities needed to achieve mission objectives. Instead, the effects of the interaction between the spacecraft and ground operators must also be taken into account. This paper describes a method, using "operations efficiency factors", to account for these effects for Mars surface missions. Typically, this level of analysis has not been performed until much later in the mission development cycle, and has not been able to influence mission or spacecraft design. Further, the notion of moving to sustainable operations during Prime Mission—and the effect that change would have on operations productivity and mission objective choices—has not been encountered until the most recent rover missions (MSL, the (now-cancelled) joint NASA-ESA 2018 Mars rover, and the proposed rover for Mars 2020). Since MSL had a single control center and sun-synchronous relay assets (like MER), estimates of productivity derived from MER prime and extended missions were used. However, Mars 2018's anticipated complexity (there would have been control centers in California and Italy, and a non-sun-synchronous relay asset) required the development of an explicit model of operations efficiency that could handle these complexities. In the case of the proposed Mars 2018 mission, the model was employed to assess the mission return of competing operations concepts, and as an input to component lifetime requirements. In this paper we provide examples of how to calculate the operations efficiency factor for a given operational configuration, and how to apply the factors to surface mission scenarios. This model can be applied to future missions to enable early effective trades between operations design, science mission planning, and spacecraft design.

I. Introduction

WHEN laying out a new mission concept, a key attribute is the duration of the primary (or "prime") mission. Commonly considered the result of how long it would take for the activities and observations which implement the mission objectives to execute on the spacecraft, the prime mission duration has implications that radiate throughout the mission concept, such as power source, component lifetime (and the testing needed to qualify components for that duration), memory sizing, communications strategies, and operations cost.

For some missions, however—and for Mars surface missions in particular—how long it takes to complete activities and observations depends on the characteristics of interactions with ground operations teams. Thus, it is important to understand how such interactions impact mission duration. To this end, we posit that for Mars surface missions, a given operations configuration—including ground operations team staffing schedules and communications patterns—has an associated "ops efficiency", a ratio indicating how often the ground operations team can interact with the spacecraft effectively. It is important to note that the word "efficiency" is used here not as a synonym for "effective", but instead as a quantifiable concept, a measureable ratio of a resource produced (plans based on timely data) to resource consumed (sols, or Martian days). This ratio can then be used in surface mission models to ensure that the interaction of ground teams with the spacecraft is taken into account when determining the prime mission duration during mission formulation.

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II. Brief Overview of Mars Surface Operations

Mars surface missions to date have had a key driving characteristic: their operations on Mars are dominated by thermal and lighting requirements that drive them to operate primarily during the Martian daytime. Thus, operators for Mars surface missions tend to plan in "Mars time", or local mean solar time. In addition, particularly for spacecraft that interact with the terrain—such as by traversing over it, or using manipulators to place instruments or dig into it—the resulting uncertainty in spacecraft state, attitude, and position after executing such "robotic" activities, coupled with less-than-complete spacecraft autonomy, means that in order to develop safe plans for the next "sol" (Martian day), the ground operations team must know the latest "robotic" state of the spacecraft. As a result, the communication patterns for both "uplink", radiating new commands to the spacecraft, and "downlink", sending telemetry (data) to Earth for the ground teams to analyze to determine a snapshot of rover state and the results of science instrument observations, are usually tuned to best fit the pattern of Martian daytime operations: generally, uplink is in the Martian morning, and downlink is in the Martian afternoon or evening. However, the actual local mean solar times (Mars local times) for communications may depend on factors such as the availability of ground antennae or the orbits of spacecraft serving as relay comunications assets. To date, Mars orbiters used for relay (Mars Global Surveyor, Odyssey, Mars Reconnaisance Orbiter, and Mars Express) have had (nearly) sun-synchronous orbits, which suited their missions' objectives well, as well as providing overflights for surface spacecraft at stable local mean solar times. Upcoming orbiter missions (MAVEN and ExoMars Trace Gas Orbiter) are planned to have non-sun-synchronous orbits, which will cause the overflight times to "walk" through the Martian day.

The ground teams operating the missions, of course, mark their schedule according to "Earth time" (wall clock time on Earth). The ground operations shift begins with the receipt of data (after latencies inherent in relaying data back to Earth either through an orbiter or via direct-to-Earth radiation). The team quickly analyzes the data to determine the critical portions of the spacecraft state for planning, including position and attitude, and the science team does a similar "quicklook" interpretation of instrument data. Based on this data and working within resource and other constraints provided by the engineering team, the science team determines the objectives for the next planning cycle (which typically covers 1-3 sols). The remainder of the shift is used to generate and review the commands implementing the approved science and engineering plan, including the commands for any robotic motion to be executed during the plan (traversing to a target or toward a new location, placing instruments on targets, etc.). At the end of the shift, the final commands are approved and scheduled to be sent to the spacecraft, either via direct-from-Earth radiation or forward-linked via a relay asset. For more detail, please refer to Mishkin, et al., "Working the Martian Night Shift". [1] On the Mars Exploration Rovers (MER) and the Mars Science Laboratory (MSL), the initial ground shift length was 17-19 hours. After roughly 90 sols on both MER[2] and MSL, the shifts were shortened enough to allow some margin between the receipt of downlink and the latest possible uplink time. This margin is key to enabling alternative, more sustainable, ground operations schedules.

III. Factors Influencing Ground Operations Scheduling

The scheduling of the ground operations team for a Mars surface mission is influenced by many factors, the primary two arguably being 1) the ability of the team to execute the planning process in the time given, and 2) cost. Folded into "cost" are several considerations: not only the number of operations shifts during a planning cycle and the number of days/week planning is being done, but also the depth of the training pipeline to cover personnel attrition as people move on to other positions or leave the project. We describe key concepts in ground operations scheduling for Mars surface missions below. (The operations scheduling discussed in this paper refers to the "tactical" planning process, which is the day-by-day (or sol-by-sol) planning process using returned data to generate the specific commands for the next planning period. There are other planning processes being conducted in parallel at different time scales—such as advanced planning to lay out observational campaigns or plan longer traverse routes, and coordination with the Deep Space Network and relay assets—but since those processes do not factor into the "ops efficiency" calculation, they are not discussed here.)

A. Why work Mars time?

First, we should define "working Mars time". The Martian sol is roughly 40 minutes longer than an Earth day, so if on the first day/sol we imagine that 8:00 AM PDT and 8:00 AM LMST (Local Mean Solar Time on Mars) are synched, then the next day, 8:00 AM LMST will fall on roughly 8:40 AM PDT, then 9:20 AM PDT the next day, and so on. "Working Mars time" is a pattern of 24/7 shiftwork such that the starting time of the shift is synched to the Mars clock (and specifically to the expected receipt of data, usually with a fixed offset to reflect when in the planning process a given role's responsibility begins). On MSL, the phrase "working Mars time" was used as a shorthand for the period of 24/7 operations where the shift start times were synched to the return of relay data; since the use of relay orbiters introduces additional latencies due to orbit geometry, data buffering, and data rerouting on the ground, and since the relay orbiters are not precisely sun-synchronous but have a slight "wobble" in their overflight times, the shift start times are not linked to a specific Mars LMST. As a result, the shift start times can move earlier or later, deviations from the overall marching-40-minutes-forward pattern. (On MER, the use of relay assets was not baselined for the return of critical/decisional data (that is, data needed for planning the next sol), so shift start times were synched more directly to the Mars clock during the period of working Mars time.)

It should be noted that working Mars time is not easy on people. [3] Besides the well-documented effects of shiftwork (meaning long-duration or off-hour shifts), the constantly-moving shift start times exacerbate these effects. Experience working Mars time on four Mars surface missions has shown that the experience is isolating, disorienting, fatiguing, and causes issues for personnel with families (whether or not they are also on a Mars time schedule—though usually they are not). Many of those who have worked Mars time have stated that it is even more difficult to work a similar schedule the second time around. After about 90 sols of working Mars time, operations teams (including science team members) have consistently demanded the relief of moving to a more sustainable schedule.

So why work Mars time at all? At the start of the prime mission, just after landing, the operations team has the least amount of experience with both the planning process and with operating the new spacecraft. Working Mars time allows the maximum duration between the receipt of downlink and the last possible uplink time for the next sol, giving the greatest amount of time to execute the planning process and review the generated plans and commands. The tactical planning process at the start of MER and MSL filled the entire available time—17-19 hours—and would not have been possible to execute except on a Mars time schedule. Additionally, two key benefits of Mars time, even as moving up the learning curve and implementing streamlined processes shortens the planning cycle shift duration, are 1) that the operations team is always using "fresh" data, newly returned from the spacecraft, and 2) the operations team is generating a new plan for every sol. Both of these conditions together increase the productivity and science return of the mission, since the spacecraft and ops team are reacting to new data as quickly and consistently as they can.

B. Why work a sustainable schedule?

As before, we should first explore what we mean by a "sustainable schedule". The most sustainable schedule would be one that looks as much like a "normal" day-to-day work schedule as possible: that is, 5 days/week, with stable shift times during usual working hours. This schedule is easiest on personnel, in that it follows well-established patterns of sleep and family interaction, allows sufficient time outside of work for sustaining activities, etc., mitigating fatigue. This schedule also enables peronnel to have part-time roles on the project, since odd operations schedules could interfere with personnel availability for other tasks even on days when the person is not on shift. Additionally, experience with various ground ops schedules for Mars surface missions, including Mars time, shows that a more "normal" (sustainable) ops schedule results in less personnel turnover, since the working schedule becomes less incentive to move to other, non-tactical tasks. Each of these factors--shorter shift durations, 5 day/week operations, normal working hours, and less personnel turnover (meaning needing fewer personnel in the training pipeline at a given time)--contribute to lowered operations cost. Personnel turnover can be additionally damaging in that it often results in the loss of corporate knowledge being readily available for the project. Anecdotally, the reduction in fatigue and disorientation found by moving to a sustainable schedule also appears to result in fewer command errors.

C. Ground scheduling "modes"

As shown in Fig. 1, the daytime Mars operations and communications opportunities (uplink and downlink, which are ideally tied to the Martian clock to maximize productivity on the surface) beat against the Earth clock, moving through the Earth day, re-synching again after a 38-day cycle. In order to move toward a sustainable schedule, two things must happen: 1) the tactical planning shift must be short enough to allow some margin, which would be used not as margin, but to allow the planning shift to "float" within the downlink-to-uplink constraint to keep the shift start times as stable as possible, and 2) in order to keep shift times within a prescribed band in the Earth day, the project must agree to give up some ability to react to new data, accepting some reduction in "ops efficiency" as compared with Mars time operations.

In order to ease the transition of the operations team into more sustainable schedules—and to help lessen the reduction in productivity associated with sustainable schedules—there were different operations schedule "modes" defined for MER and MSL. These were: Mars time (as described in section III.A), Modified Earth-time 7 days/week, and Modified Earth-time 5 days/week. (An additional ops schedule mode could be a strictly "Earth time" schedule—that is, a normal day-to-day office schedule. To date, trades between moving to strictly Earth time and the resulting loss in ops efficiency, versus the costs associated with the Modified Earth-time 5 day/week schedule, have been decided in favor of staying with the 5 day/week Modified Earth-time schedule indefinitely.)

"Modified Earth-time" can be described as follows: the ground operations planning cycle has a given shift length (duration), an earliest start time, a latest start time (derived from a latest end time), and a preferred start time. As the 38-day cycle progresses, the relative relationship of the ground operations planning shift and the downlink-to-uplink window precesses though the following series: "tight" sols, "nominal" sols, "slide" sols, "restricted" sols, and finally a "soliday" to re-synch the Earth and Mars time schedules. Nominal sols are those in which the preferred start time for the ground operations shift is sufficiently after the receipt of downlink so the shift can begin normally, and can complete comfortably before the uplink time—in other words, the preferred ground operations shift fits perfectly within the downlink-to-uplink window. As the downlink time marches forward through the Earth day, receipt of downlink happens too close to (or after) the preferred shift start time. On those days, the shift start time "slides" later to accommodate the downlink, so these planning days are called "slide sols". This continues (with the start time sliding later), until the latest allowable start time is reached. Past this point, the tactical planning shift can no longer accommodate the moving downlink time, so the start time "snaps back" to the preferred start time. During this period, and until the uplink moves late enough in the day so that a shift starting at the earliest allowable start time can fit before the uplink, the planning cycle is called "restricted sols". "Tight sols" occur when a tactical planning shift starting at the earliest allowable start time can "just" fit (with necessary margin) before uplink, and until the uplink moves late enough so a shift starting at the preferred start time can again fit comfortably, back to nominal sols. A "soliday"—a no-planning day on Earth—occurs between restricted sols and tight sols, and is a result of the re-synching of the Earth-time planning cycles and Mars sols. (In other words, due to a Mars sol being slightly longer than an Earth day, there are 37 sols planned during a 38-day Modified Earth-time cycle.) 7 day/week and 5/day week simply describe how many days per week the Modified Earth-time schedule is worked; the 5 day/week schedule also generally includes days off for holidays, and is accomplished by planning up to 3-sol plans on Fridays to cover weekends (and using stale data to stack 2- to 3-sol plans several days in a row for longer holiday weekends, for example).

The reduction in ops efficiency due to 7 day/week Modified Earth-time schedules comes from the restricted sols. In all other cases, data from the prior sol is used to plan activites for the next sol. However, during restricted sols, the downlink is received too late to be used during the shift (since the state of the spacecraft must be known at the start of the shift to properly feed into the tactical planning and command-generation process). Thus, the tactical planning process must use stale data—data from a sol earlier than the immediately-prior sol—in order to estimate the state of the spacecraft. Since robotic activities (traverse and manipulation, for example) can only be safely planned if the state of the spacecraft is known, these types of activities are restricted during restricted sols (hence the nomenclature). Note that activities can be planned that do not affect the state of the spacecraft relative to the terrain (or that don't violate other restrictions on changing spacecraft state during this period), such as remote sensing from mast-mounted instruments, so the spacecraft need not stay completely quiescent. Also, note that if such activities are planned for a given sol n, then the "stale" data from sol $n-1$ accurately represents the robotic state of the spacecraft, which enables safe planning of robotic activities on sol $n+1$, even if that planning cycle is still restricted. Thus, robotic activities can still be planned during restricted sols, basically every-other-sol. (The nomenclature for this distinction is "constrained sols", during which no robotic activities can be safely planned, and "unconstrained sols", during which the data on hand accurately represents the robotic state, so robotic activities can be safely planned. Nominal, slide, and tight sols are automatically unconstrained, so the distinction is usually reserved for restricted sols.)

5 day/week Modified Earth-time schedules further reduce ops efficiency due to the forced restrictions on robotic activities (all but 1 sol are constrained) on weekend plans, and the use of stale data (which may cause entire multi-sol plans to be constrained) for plans covering (or in anticipation of) holidays. (Due to the added complexity, and time required to generate and review the plans and commands for additional sols, multi-sol plans for weekends and most holidays are limited to 2- or 3-sol plans. For occasional periods, such as solar conjunction—during which communication with the spacecraft is suspended—and very long holiday recesses, longer multi-sol plans may be generated in a separate process apart from the tactical planning process.)

It should be noted that the tactical planning shift duration has a significant effect on the length (within the 38-day cycle) of each of these planning cycle types. A shorter shift duration provides more margin relative to the length of the downlink-to-uplink window, which in turn enables more slide sols (since a later "latest allowable start time" would correspond to the same "latest allowable end time" for a longer shift) and more nominal sols (since a shorter shift would more quickly be able to fit between the preferred start time and uplink as uplink marches forward), resulting ultimately in fewer restricted sols.

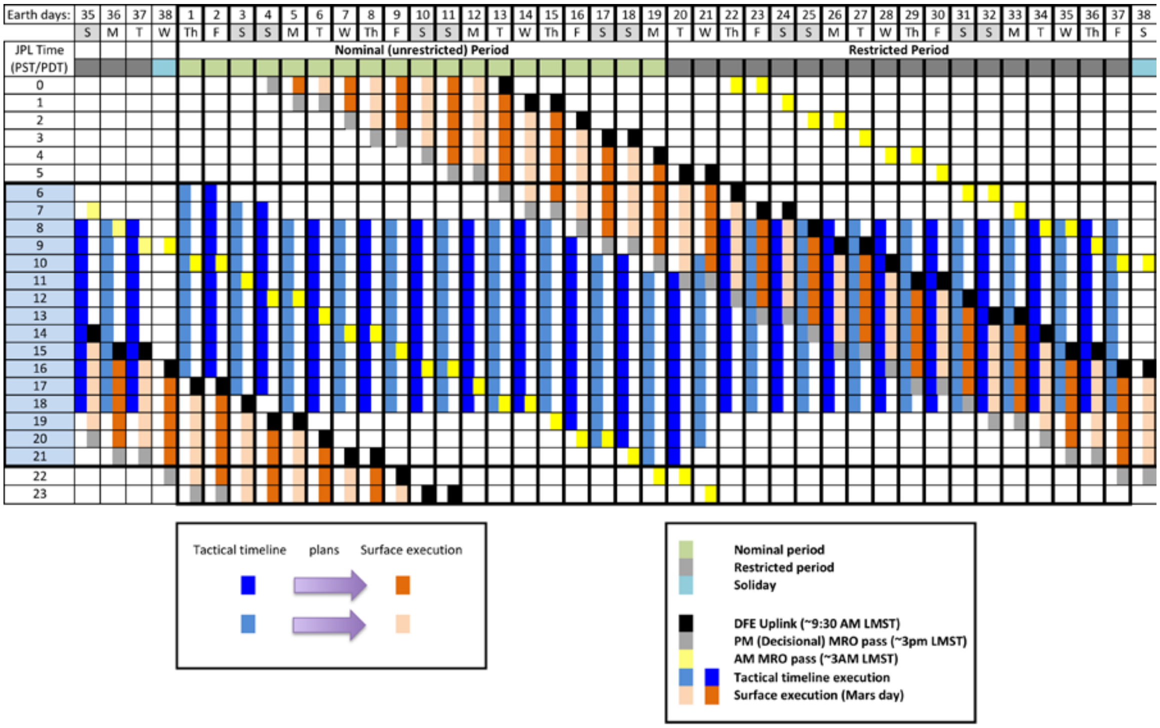

Figure 1. 7 Day/week Modified Earth-time schedule (38-day cycle). *This illustration shows the progression of the decisional downlink (light grey) and uplink (black) times—which are keyed to fixed Martian local mean solar times—through successive Earth days. For simplification on this figure, tight, nominal, and slide sols are all designated "Nominal (unrestricted)" (green), restricted sols are dark grey; the soliday is turquoise. Mars red designates the period of Martian daytime operations on the surface of Mars; deep blue represents the Earth tactical planning shift. Dark deep blue shifts plan dark Mars red sols; light deep blue shifts plan light Mars red sols.*

D. Control Centers

Finally, the number and location of operations control centers can affect ops efficiency. Control centers are loci of operations that host tactical planning processes for periods of time, to which ground operations schedules are synched (that is, remote participants—whether science team members or even engineers physically located at other control centers—will dial in to tactical planning process meetings synched to the local time zone of the active/primary control center on a given day). If control centers are placed appropriately—and staffed sufficiently with local operators so as to mitigate any human factors detriments due to shiftwork across time zones—then ground ops schedules and handoffs between control centers can be planned to better mimic a Mars-time operations schedule, even while using more sustainable Modified Earth-time schedules at each control center.

IV. Ops Efficiency

Pulling all of these factors together—Mars operations patterns and ground operations patterns—allows one to calculate the ops efficiency. First, we define an "ops configuration" as a particular specification all of the characteristics we described above: communications times—the times of receipt of decisional downlink and last possible uplink times--including one way light time and latencies, number and time zone of control centers, tactical planning shift duration, and details of the ground operations mode for each control center (including holidays, if applicable). The ops efficiency is, simply stated, the percentage of sols that are unconstrained (including nominal, slide, tight, and unconstrained restricted sols) for a given ops configuration. As noted previously, the ops efficiency is a quantifiable characteristic of a particular ops configuration, and can be used in various ways, including comparing the ops efficiency of ops configurations, and using the ops efficiency in surface mission scenario modeling to ensure Earth-Mars time phasing effects are properly accounted for in activity durations.

Implicit in the current ops efficiency calculation are several key assumptions, which should be noted particularly when calculating ops efficiency for missions early in formulation. (For missions in early phases of development, ops efficiencies can be estimated using simplified models of the various characteristics, such as relay overflight times and latencies, in order to explore the effects of mission design choices.) The major assumptions are as follows:

1) Mars surface operations follow the pattern of uplinked commands followed by the primary operations period (including any changes to the robotic state), followed by the decisional downlink carrying data to feed into the next planning cycle.
2) All decisional data (data needed for the next planning cycle) fits into the available downlink bandwidth, and is successfully downlinked.
3) All uplinks are successful.
4) All planning cycles fit within the specified ground operations shift durations.

These assumptions are predicated on the idea that the primary operations period on the Martian surface for spacecraft is driven by lighting and thermal considerations (and power, for solar-powered spacecraft), and that therefore communications strategies will be tuned to maximize the use of the Martian daylight period as much as possible; and secondly, that in the absence of advanced on-board autonomy, ground-in-the-loop (having ground operators make key decisions for the spacecraft, in the form of commands) will be required for robotic activities—as well as for such activities as science instrument target selection and observation planning—and thus decisional data needed to facilitate planning will be tailored to fit the available bandwidth. Failed communications could be treated similarly to other estimated loss rates, by including margin in any scenario models. Alternatively, if a particular relay asset, for example, is known to have a given downlink failure rate, that information could potentially be folded into the ops efficiency calculation to compare across assets. Finally, it is assumed that the shift duration specified is actually achievable on an ongoing basis by the ground operations team at that point in the mission.

Again, one should be careful not to confuse ops efficiency, which is a measureable property of an ops configuration, with the effectiveness or productivity of an operations team, which is dependent upon such factors as the effectiveness of operational processes, the level of training of the operations team members, the complexity of the mission objectives, specific characteristics of the landing site and environs, and (importantly) the operability (or lack thereof) of the spacecraft.

A. Calculating ops efficiency

At the current time, ops efficiency is calculated by a brute force method, via an Excel spreadsheet. The spreadsheet captures the key characteristics of the ops configuration, including downlink receipt times in appropriate Earth time zones, the last possible uplink times (also in appropriate Earth time zones), and shift duration, for a representative set of Earth days. For the brute force method, 500 planning cycles was chosen, as a number that could provide reasonable statistics—covering almost 2 Earth years' worth of weekends and holidays—while still being workable manually. For the Earth days in the spreadsheet, the specified ground operations mode is applied for the control centers being considered. The spreadsheet gathers statistics of interest about the ops configuration, including the number of 1-, 2-, and 3-sol plans, the numbers of each of nominal, slide, tight, restricted, and constrained sols, and computes the ops efficiency (the ratio of unconstrained sols to the total number of planning cycles).

An alternative method for finding a quick estimate of ops efficiency is to lay out a single 38-day planning cycle for an ops configuration. Although this method will not include holidays off for 5 day/week operations modes, the estimates found using this method are within a few percent of those calculated using the brute force method (assuming holidays are working days). Although these estimates don't have the fidelity of the brute force method, they can still be useful for quick comparisons of ops configurations.

Work is in progress to develop a program to aid in the calculation of ops efficiency and the other statistics of interest, without the use of a spreadsheet or manual scheduling. This program will prove particularly useful for Mars surface missions in current development, such as Mars 2020, as it trades various communications options to deal with the aging of the existing Mars relay assets, and to missions such as MSL studying options for balancing reduced operations cost with maintaining ops efficiency in extended mission.

B. Results for representative missions

Sample ops efficiencies for specific ops configurations—that have been computed for Mars 2018, the proposed Mars 2020, and MSL—appear in Table 1 below.

Table 1. Ops efficiencies for specific ops configurations. *Ops efficiencies marked with † are quick estimates.*

Mission	Downlink	Uplink	Shift length	# Ctrl Ctrs	Ground Operations Mode	Ops Efficiency
Mars 2020	15:00 LMST	9:30 LMST	8 hrs	1	Mars-time	100%
Mars 2020	15:00 LMST	9:30 LMST	8 hrs	1	Modified Earth-time, 7 days/week: 6am earliest start, 8pm latest end	83.50%
Mars 2020	15:00 LMST	9:30 LMST	8 hrs	1	Modified Earth-time, 5 days/week: 6am earliest start, 8pm latest end	60%†
MSL	15:00 LMST	9:30 LMST	8 hrs	1	Mars-time	100%
MSL	15:00 LMST	9:30 LMST	10 hrs	1	Modified Earth-time, 7 days/week: 7am earliest start, 11pm latest end	78.16%
MSL	15:00 LMST	9:30 LMST	10 hrs	1	Modified Earth-time, 5 days/week: 7am earliest start, 11pm latest end	57.52%
MSL	15:00 LMST	9:30 LMST	9 hrs	1	Modified Earth-time, 7 days/week: 6am earliest start, 8pm latest end	69.74%
MSL	15:00 LMST	9:30 LMST	9 hrs	1	Modified Earth-time, 5 days/week: 6am earliest start, 8pm latest end	58.12%
MSL	15:00 LMST	9:30 LMST	9 hrs	1	Modified Earth-time, 5 days/week: 5am earliest start, 9pm latest end	59.72%
MSL	15:00 LMST	9:30 LMST	9 hrs	1	Modified Earth-time, 6* days/week: 5am earliest start, 9pm latest end; *work unrestricted weekends & holidays	61.52%
MSL	15:00 LMST	9:30 LMST	11 hrs	1	Modified Earth-time, 6* days/week: 6am earliest start, 12am latest end; *work unrestricted weekends	73%†
MSL	15:00 LMST	9:30 LMST	11 hrs/ 8 hrs	1	Modified Earth-time, 5 days/week: 6am earliest start, 12am latest end; select use of short traverse-only shift during restricted sols	73%†
Mars 2018	Non-sun-sync; 14 Mars min earlier each sol	9:00 LMST	10 hrs	1 or 2	Mars-time	92.1%
Mars 2018	Non-sun-sync; 14 Mars min earlier each sol	9:00 LMST	10 hrs	1	Modified Earth-time, 7 days/week: 7am earliest start, 11pm latest end	69.4%
Mars 2018	Non-sun-sync; 14 Mars min earlier each sol	9:00 LMST	10 hrs	1	Modified Earth-time, 5 days/week: 7am earliest start, 11pm latest end	53%
Mars 2018	Non-sun-sync; 14 Mars min earlier each sol	9:00 LMST	10 hrs	2 (PT, CET)	Modified Earth-time, 7 days/week: 7am earliest start, 11pm latest end	83.4%
Mars 2018	Non-sun-sync; 14 Mars min earlier each sol	9:00 LMST	10 hrs	2 (PT, CET)	Modified Earth-time, 5 days/week: 7am earliest start, 11pm latest end	60%

As can be seen in the results, the use of non-sun-synchronous orbiters for decisional downlink relay drastically reduces ops efficiency (even driving Mars-time ops efficiency below 100%!). This effect, however, can be mitigated by having two control centers spaced around the globe. Surprisingly, widening the ground operations window (earlier allowable start time and later allowable end time) did not always help significantly raise efficiency, especially when combined with weekends and holidays off. The use of quick ops efficiency estimates showed that the ops efficiency of working weekends during unrestricted periods is approximately the same as the ops efficiency of adopting shorter, traverse-only (no additional science) planning cycles without working weekends, enabling a more sustainable schedule while maintaining ops efficiency during a push to achieve traverse distance on MSL.

C. Uses for ops efficiency

As described earlier, the ops efficiency of given ops configurations has several important uses. For example, during mission formulation, it is important to determine whether the mission objectives can fit within the prescribed duration of the prime mission (or alternatively, how long the prime mission should be to enable the mission objectives to be met). Using appropriate ops efficiencies in the surface scenario models ensures that the effects of Earth-Mars time phasing, operations schedules, and communications strategies are appropriately included in the mission duration estimation, and can serve to highlight where prioritization of objectives and mission design focus may be warranted. Ops efficiencies were included in surface scenario modeling to great effect for early formulation efforts for the now-canceled Mars 2018 mission, and by the Science Definition Team for the proposed Mars 2020 mission.[4] Ops efficiencies can help give more reasonable estimates of mission productivity, by factoring in communications strategies and human factors considerations early in mission design.

Additionally, ops efficiencies are being used on Mars 2020 to compare communication strategy trades, including the effects of non-sun-synchronous orbiters for relay and direct-to-Earth options. Ops efficiencies also highlight the effects of operability design choices, such as adding on-board autonomy or other methods to help reduce the need for ground-in-the-loop. Finally, ops efficiencies can be used—as they have been on MSL—to help compare and evaluate operations scheduling strategies for specific needs, such as reducing cost in support of extended mission proposals or for effectively scheduling operations "surges" to achieve particular objectives within a specified time.

V. Conclusion

Ops efficiency captures a key measureable aspect of Mars surface missions: the availability of single-sol turnaround of operations plans, given specific communications patterns and ground scheduling mode. This concept can be used to more realistically inject operations and human factors considerations into mission design trades, and is valuable not just for early mission formulation (though it is certainly useful there) but during later project phases as well. As an example, ops efficiency can provide a means of quantifying the mission return benefits of specific operability or performance improvements in the spacecraft design, such as increased traverse autonomy.

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