Productivity Challenges for Mars Rover Operations

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Abstract

Achieving consistently high levels of productivity for surface exploration missions has been a challenge for Mars missions. While the rovers have made major discoveries and accomplished a large number of objectives, they often require a great deal of effort from the operations teams and achieving objectives can take longer than anticipated. This paper describes the early stages of a multi-year project to investigate solutions for enhancing surface mission productivity. A primary focus of this early stage is to conduct in-depth studies of Mars Science Laboratory science campaigns to gain a deeper understanding of the factors that impact productivity, and to use this understanding to identify potential changes to flight software and ground operations practices to increase productivity. We present the science campaigns we have selected along with a conceptual model of how surface missions achieve objectives that is used to guide the study. We also provide some early thoughts on the technologies, and their interactions, which we believe will play an important role in addressing surface mission productivity challenges.

Introduction

The Curiosity rover has been exploring Gale Crater and Mount Sharp since its landing in August 2012. During this time, the Mars Science Laboratory (MSL) mission has accomplished many significant objectives. It has achieved the success criteria for the prime mission, collected evidence that indicates Mars was once habitable, collected over a dozen samples and driven more than 12 kilometers (Grotzinger et al. 2015; Vasavada et al. 2014). Curiosity is currently in its extended mission and continues to make new discoveries as it explores Mount Sharp.

While the Mars rovers, including Spirit, Opportunity and Curiosity, have demonstrated an incredible ability to survive far beyond their designed lifetimes, they still represent limited opportunities to explore the planet. As such, there is great interest in getting the most out of these landed assets over the course of the missions.

Maintaining high levels of productivity for the Curiosity rover is challenging. While the operations team has made significant accomplishments with the rover, doing so often requires a large amount of human effort in planning, coordinating, sequencing and validating the development of command products for the rover. Further, limitations in communication opportunities and anomalies on the vehicle can sometimes cause delays in accomplishing the team's objectives. These productivity challenges can result in the underutilization of the vehicle's resources.

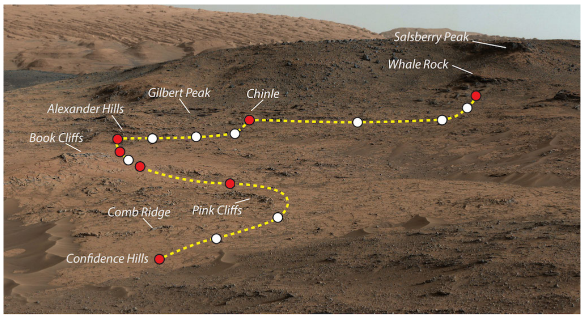
We are conducting a multi-year project to address these productivity challenges. Beginning with in-depth case studies of key MSL campaigns, we will develop a better understanding of the factors that promote and hinder surface mission productivity. Based on the findings from the study, we are developing designs for flight software and ground operations practices to address these challenges. The designs will be prototyped on research rovers and evaluated in realistic operations scenarios.

We are currently in the first year of the project, conducting the MSL case studies. The remainder of this paper describes the case studies we have selected for our investigation with motivations for why we think they will yield interesting results. Next, we provide an overview of the mission operations process to provide context for the discussion of mission productivity. We then provide a conceptual model of how mission objectives are accomplished. The model provides guidance in the collection and analysis of data in the case studies and highlights some of the factors that may influence productivity. Finally, we provide our early thoughts on the types of changes to flight software and ground operations that we anticipate will be important in attaining high levels of surface mission productivity.

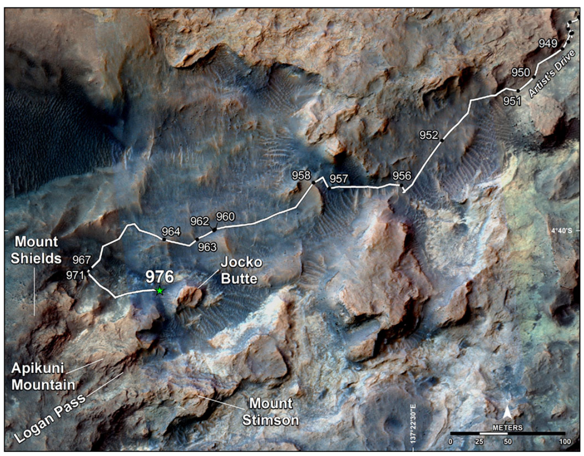
Illustrative Campaigns

We are conducting an in-depth study of some of Curiosity's science campaigns to help increase our understanding of the factors that contribute to and detract from surface mission productivity. For each campaign, we are examining how the operations team decides what to accomplish each day, how well these objectives are achieved and how results from one day feed into and inform objectives for the next.

Figure 1 shows the campaigns that we have selected for study. Curiosity began exploring Pahrump Hills (Figure 1 (a) in the fall of 2014 (Stack et al. 2015). Pahrump Hills is an interesting case study for multiple reasons. The light-toned outcrop of Pahrump Hills was the first exposure



(a) Pahrump Hills (Curiosity Mastcam)



(b) Artist's Drive (Mars Reconnaissance Orbiter HiRISE)

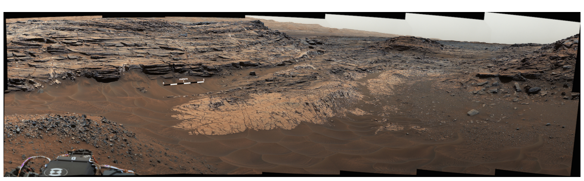

(c) Marias Pass (Curiosity Mastcam)

Figure 1: Examples of Curiosity's science campaigns.

of bedrock making up the base of Mount Sharp that was encountered during the mission. The campaign was also significant in the way in which the exploration of this formation was conducted. The science team decided to conduct a "walkabout", a practice used by field geologists when studying unexplored geological areas on Earth. The team made multiple passes of the area with each pass informing a subsequent, more detailed study. We chose to focus on the first walkabout which explored the region with primarily remote sensing instruments (mast-mounted imagery and spectroscopy) in order to identify locations to return to for more detailed follow-up study with arm-mounted instruments. Another interesting factor was the geography of Pahrump Hills was conducive to developing a strategic plan for the initial walkabout. The sloping hills made it possible to see nearly the complete formation from a single panoramic image allowing scientists and engineers to plan a route to explore the area.

After completing investigations at Pahrump Hills, Curiosity departed the area in the spring of 2015 with the objective to reach higher levels of Mount Sharp for continued exploration. Curiosity followed a route referred to as Artist's Drive, shown in Figure 1 (b) (Jet Propulsion Laboratory Press Release 2015). Along the way, the science team conducted a science campaign to capture images of the surrounding topography in order to build a record of the stratigraphy (i.e., layering and structure) of the sedimentary rock layers exposed in the valley walls. The orbital imagery provided by the Mars Reconnaissance Orbiter's HIRISE instrument enabled the team to identify locations where gaps in the surrounding terrain provided the opportunity for imaging the far terrain.

While the orbital imagery enabled the team to develop a strategic route for driving through Artist's drive, the geography of the region made it more challenging for day to day (also referred to as tactical) driving. The orbital data provides good information about the general terrain the rover will encounter, but it is not sufficient resolution for the actual drive path planning. Instead, images acquired from the end of the previous drive are used, in conjunction with orbital data, to plan the next drive. Ridges and valleys in the surrounding terrain often prevented the rover from getting a good view of the terrain in which it would be driving the next day, and wheel wear concerns limited the desirability of using onboard autonomous hazard detection to extend drives into unseen terrain. This often made it difficult for the engineers to plan the next drive path.

Along the route toward higher levels of Mount Sharp, Curiosity took the opportunity to explore an area where the Murray Formation (the type of rock from Pahrump Hills) came into contact with an overlying geological unit called the Stimson Unit. The contact was explored in an area named Marias Pass, shown in Figure 1 (c) (Milliken et al. 2016). This campaign has interesting similarities and contrasts with the earlier Pahrump Hills campaign. Both campaigns sought to explore and characterize a geological area. However, the more challenging terrain in the area and discoveries made during exploration resulted in a more dynamic campaign than the Pahrump Hills walkabout cam-

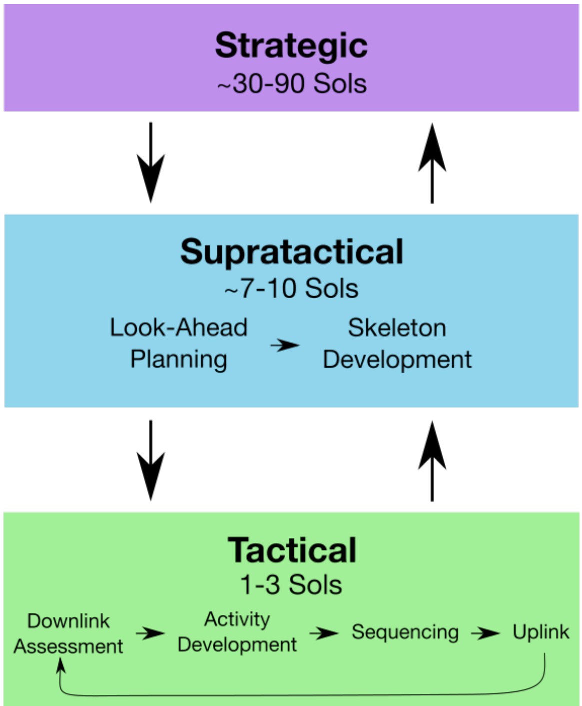


Figure 2: Overview of MSL operations.

paign.

Overview of MSL Mission Operations

One of the challenges a surface mission has compared to an orbital mission is that a surface mission is impacted more significantly by a prior unknown and changing environmental conditions. While orbital imagery provides valuable information to guide activity, it does not capture all the conditions that affect the rover. For example, while orbital imagery may indicate that exploring a particular region is promising to achieve a science objective, the specific science targets are not known until additional data is collected from the rover itself, such as images from its mast-mounted cameras. Further, orbital data is insufficient for fully predicting specific terrain conditions that will impact the rover's traversability and its able to perform close-contact operations on targets of interest.

As such, surface operations must be reactive and respond to the results of activity carried out during the previous sol (Martian day). This daily planning activity is referred to as "tactical" operations and is patterned after the tactical operations developed for the Mars Exploration Rovers (Mishkin et al. 2006).

MSL operations are organized into three major phases: strategic, supratactical and tactical (Chattopadhyay et al. 2014). Figure 2 illustrates the relationship among these phases. These processes are structured to enable the team to achieve long-term science objectives, managing the limited rovers resources, while still responding to the dynamic nature of surface exploration.

Strategic planning focuses on developing long-term plans, typically spanning weeks or months, to achieve high-level objectives. For example, in the Pahrump Hills campaign from Figure 1 (a), the strategic plan spanned several months and specified a multi-pass approach to exploring the region in order to achieve the high-level objectives of performing a comprehensive study of the formation. Strategic planning for the Artist's Drive campaign (Figure 1 (b)) included the development of a Strategic Traverse Route (STR) to provide guidance for selecting paths for the rover on its longer-term objective to reach higher levels of Mount Sharp. These strategic plans provide vital guidance in achieving mission objectives, but they are not directly executable. They must be adapted to take into account the current conditions and adjusted to respond to unanticipated conditions as the rover explores the environment. For example, while the STR provides guidance on the direction the rover should travel, the actual tactical routes may deviate from the route in order to respond to local terrain conditions. And in some cases, significant alterations to the STR were required when a particular path was discovered to be non-traversable or in cases where unexpected science objectives were identified.

The supratactical stage provides a bridge between the long-term strategic plan and the day-to-day, highly reactive tactical process. The process is designed to coordinate the complex science instruments and manage the constraints and resources required to conduct campaigns. The supratactical process produces "look-ahead plans" which span several sols, typically a week, of activity. These plans help maximize the use of vehicle resources. For example, if an energy-intensive, multi-sol sampling experiment is coming up, the look-ahead plan provides guidelines on how much energy can be used each sol of operations. The process also helps with coordination among the large science team spread across the globe.

The process feeds into the tactical process by delivering a "skeleton" plan for each sol of tactical planning. The skeleton provides the tactical team with the major objectives for the plan, e.g. drive toward a particular location, or perform close-contact operations. It includes a rough structure of the activities, including coordination of science activities around communications windows and other engineering activities and guidelines on how much resources, such as energy, time and available data volume, can be expended during the execution of the plan.

The tactical planning process forms the highly reactive phase of surface operations. It includes an assessment of the state of the vehicle and the performance of the previous plan's activities. During activity development stage, specific science and engineering objectives are identified based on the high-level objectives of the current campaign and guidelines provided in the skeleton plan. The developed activity plan is translated into sequencing command products to be executed on the vehicle. These command products are verified, reviewed and delivered for uplink to the rover.

Unlike the Mars Exploration Rovers (MER) mission, which included automated planning ((Bresina, Ari K.J̃nsson, and Rajan 2005)), the MSL mission does not currently include automated planning to assist in activity plan development. Instead, MSL operators employ a combination of helper scripts and user-interface operations to support plan development, both as part of supratactical and tactical operations. Helper sequences are used to build the for a variety of purposes including, laying out communication windows according to the overflight database, placing activities to representing turning on and off the CPU, and generating heating activity per the appropriate thermal table. User-interface support includes support for laying out activities back-to-back, snapping an activity to the start or end of another and flagging errors when the activity plan violates rules as defined in the activity dictionary. As Bresina et al. observed, this type of mundane planning support is often more valuable for operations plan development than complex goal achievement.

Factors Impacting Surface Mission Productivity

In general, when we speak of mission productivity, we are referring to how effectively the operations team is able to achieve their objectives. This can include how much effort is required by the team to accomplish a given objective as well as how long it takes, e.g., number of sols, to achieve objectives.

Given the key role of objectives on productivity, we began our case study design by developing a conceptual model, shown in Figure 3, of how the team achieves objectives in a surface mission. Several of the authors have worked surface operations on the MER and MSL missions and this model is based on the authors' experience. During the case study, we will be seeing how well the model explains the data observed in the case study as well as collecting feedback in interviews with other operations personnel.

The general flow of the diagram begins with the team identifying candidate activities that can be used to accomplish their intent. These activities are developed and refined during operations planning until a set of command products is ready to be uplinked to the vehicle. The vehicle executes these activities and produces results which are conveyed back to Earth through telemetry and data products. This information, in turn, is used to support the development of subsequent activities and, potentially, new intent. The crossed out activities illustrate typical stages in the conceptual model in which activity is limited in some way. During operations planning, this can include restricting the scope of an activity, deferring an activity to a later planning day or even descoping an activity entirely. During execution, it can include partial or complete failure of an activity. The following subsections describe each stage and the factors that can limit productivity in more detail.

Both the Supratactical and Tactical team, from Figure 2, perform steps (A) through (C) of Figure 3. The Supratactical team makes these assessments when deciding what activity to include in the high-level look-ahead plan, and feeds this information to Tactical through the skeleton plan. The Tactical team makes similar decisions with the detailed tactical plan, taking into account the latest data from the vehicle.

Step (A): Activity Development

The diagram begins with Activity Development, in Step (A), where the team considers activities that could be performed that would contribute toward achieving their objectives. Objectives may be science objectives, such as characterizing a geological formation, or engineering, such as performing a vehicle maintenance operation of subsystem inspection.

In terms of the operations timeline discussed in the previous section, Activity Development can occur as part of the Supratactical timeline, delivered to Tactical in the Skeleton plan, or during the early stages of the Tactical timeline.

Throughout the planning process, the team makes use of their knowledge of the vehicle's capabilities to help develop command products that the rover will be able to achieve. In the Activity Development stage, this knowledge is used to help determine if an activity is feasible given the abilities and limitations of the science instruments and other actuators. This includes, for example, understanding the detection sensitivity of science instruments and knowing the range of slopes the mobility system can safely traverse. At times, the team will use their vehicle model to come up with creative new ways of using the vehicle's capabilities in ways not previously considered. For example, after landing the team developed methods for driving and performing arm operations with sample cached in the sampling system. In other examples, the team developed a technique for using the MAHLI instrument as a goniometer (Johnson et al. 2015), as well as using the rover's inertial measuring unit to perform a gravimetry survey (Lewis, Peters, and Gonter 2016).

Depending on the type of activity, varying levels of knowledge of the current state of the vehicle may be required. For example, in order to select specific targets for the mast-mounted instruments, knowledge of the position the rover will be in along with navigation images of the surrounding terrain is required. Similarly, activities related to using the arm in close contact with the surface typically require up to date knowledge of the rover and the terrain. In contrast, many activities such systematic survey imagery and atmospheric measurements do not require as extensive knowledge of the current state of the vehicle.

The level of rover state knowledge required to accomplish an activity may prohibit certain activities from being accomplished on a given sol. The amount of knowledge about the state of the vehicle may depend on the downlinked data from the previous plan as well as activity in the current plan. For example, the downlink which contains the latest information about the state of the rover from the prior plan may be delayed, or the communications window between the rover and relay orbiter may have not transferred sufficient data to support all the desired activity. Or, the current plan may include an event that changes the state of the vehicle, e.g. by driving, such that insufficient state knowledge will be available for performing certain activities, e.g. ground-targeted imaging, after the event.

The rover typically performs activities that result in significant changes to its state during the daytime. There are usually one or two communication windows with relay orbiters during the latter part of the day which allow the rover to relay its latest state and other collected data to Earth. Un-

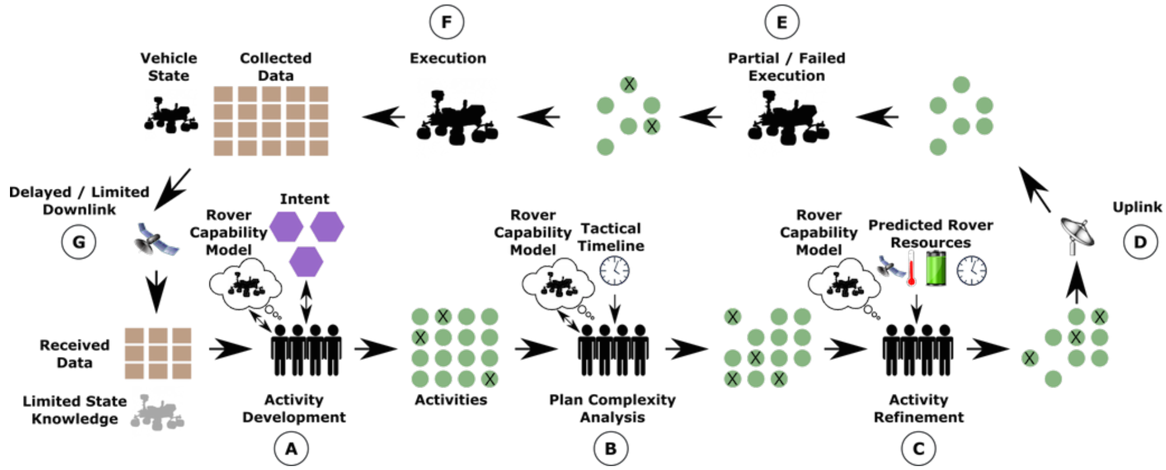


Figure 3: Factors impacting surface mission productivity.

der what is referred to as "nominal" operations, this data will be received by the operations team in the morning on Earth. The team on Earth will then have all day, during the rover's night on Mars, to develop command products that will be sent to the rover during the next morning on Mars. Mishkin has referred to this as working the Martian night shift since the operations team works during the Martian night (Mishkin et al. 2006).

A significant factor in the availability of vehicle state knowledge is the relative duration of a day on Earth and a day (aka sol) on Mars. A Martian sol is approximately 40 minutes longer than an Earth day. As such, if the operations team wishes to continue to work during the Martian night, they must continually shift the times in which they work on Earth. For example, if the team starts their shift at 8:00am one day, they would start their shift at 8:40am the next. Subsequent shift start times would be 9:20am, 10:00am, 10:40am, etc. Over the course of about a month, the team will have transitioned their shift start times around the clock. This mode of operations is referred as "working Mars time" and is highly taxing to the team. Due to the stress this mode of operations places on the team, the MER and MSL missions limited Mars time operations to the first 3 months of the mission.

The vast majority of the surface mission is conducted with the team restricting operations to the daytime on Earth. The consequence is that the operations team is often out of sync with the activity of the rover on Mars. Figure 4 illustrates the impact this can have on the data available to the team during planning. In the diagram, the end-of-day relay from the rover arrives on Earth during the night. If the team had still been working Mars time operations, they would arrive to work at this point and begin the tactical process. Instead, the team begins later in the day. Meanwhile the rover is waking up for its next Mars day. The team on Earth will not have sufficient time to develop a new set of command products by this time. Instead, by the time the team has completed the tactical process, they must wait for the next Mars morning to uplink the products to the vehicle.

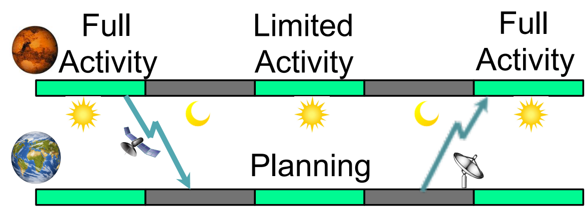


Figure 4: Mars activity vs. Earth planning.

This often limits what the team can command the vehicle to do during the middle sol of Figure 4. If the vehicle were allowed to make significant changes to its state, in particular driving to a new location, this would significantly limit the types of activities the team could command on the subsequent sol. These limited activity sols are referred to as "restricted sols" because the latency of data often restricts the type of activity the team can perform.

A similar situation arises when the team takes days off for weekends and holidays. In these cases, the team will create plans that span multiple sols (aka multi-sol plans). Again, activities that result in significant changes to vehicle state are limited since they will impact the activity that can be done in later sols of the plan.

Step (B): Plan Complexity Analysis

Step (A) discussed how the activities considered depend on the general capability of the rover and the team's knowledge of its state. In Step (B), the team considers the complexity involved in implementing the activities under consideration. As with Step (A), this step may begin with Supratactical planning and continue into the early stages of Tactical operations. The purpose of this stage is to help ensure the team does not take on more activities than can be completely planned and validated during the scheduled shift duration. If the team attempts to perform too much activity it may result in the team not completing the tactical timeline and thus risk missing the next uplink deadline. Or it could mean overloading the team which could lead to mistakes.

As such, the team carefully evaluates the activities it chooses to work on such that they can be completed during the tactical timeline. It is extremely challenging to pick an appropriate set of activities that allows the team to maximize what can be accomplished during the tactical shift without exceeding the capacity of the timeline. It requires a lot of experience and good judgment to make these decisions. Further challenging the decision making is the fact that what can fit in the tactical timeline is continually changing. The first time a new type activity is performed will require more focus and effort from the team. But after that type of activity has been performed several times, it may consume much less of the timeline. New ground tool developments can also result in increasing the capacity of the tactical timeline.

Step (C): Activity Refinement

During Activity Refinement, Step (C), the team takes into account the vehicle resources that are required to perform the proposed activities. The resources the team considers include energy, data volume and time available to perform activities. This stage uses models of the rover and activities to make predictions about the amount of resources that activities will consume and the amount of resources available on the vehicle.

Some of the resource constraints are more or less fixed. For example, the team avoids depleting the battery below a certain level and filling up the data product file system. Other constraints are more transient. For example, the Supratactical team often provides guidelines on the battery state of charge to maintain at the end of the plan. This end-of-plan battery constraint will vary from plan to plan, depending on the activity in the Supratactical look-ahead plan. Similarly, the team may self-impose tighter data collection constraints on itself in preparation for data intensive plans that are known to be upcoming in the near future.

The fidelity of the models used in the stage of operations play an important role. Missions tend to be conservative in their estimates to avoid inadvertently exceeding available resources. The model may overestimate the time and energy consumed by an activity, e.g., by allocating an overly generous margin of time around it. As a consequence, this stage may over-prune activities because the model predicts they would exceed resource constraints when in practice there may have been sufficient resources available.

Step (D): Uplink

Given the complexity of communicating with a tiny robot on a distant, spinning planet millions of kilometers away, the missions have a remarkably reliable channel for sending command products to the rover. However, problems can arise that result in loss of activity during uplink. Noise encountered on the millions of kilometers trip can corrupt the signal beyond the means of error correction codes to correct. Equipment failures on Earth stations can occur with insufficient time to repair before the uplink window. In general, the amount of data required to uplink is very small compared to the amount of data downlinked from the rover. However, there are still rare situations in which the capacity of an uplink window is insufficient to transmit all the desired command products. In each of these cases, some or all of the commanded activity can be lost.

Steps (E) and (F): Execution

After receiving command products from Earth, the rover begins executing the new plan and collecting new data. The commands products are mainly in the form of sequences, files containing lists of commands to execute.

In the large majority of cases, execution proceeds as expected and the rover is able to achieve the desired results. At other times, activities may have partial success or completely fail. There are a variety of causes of unsuccessful execution. Sometimes the command product may have included an uncaught command error which results in a problem during execution. Other times, the current state of the vehicle may have been unexpected. Sometimes sequences are written to take into account uncertainties in the state of the vehicle, but such sequences add complexity to develop, consuming the capacity of the timeline, and the expressivity of the sequencing language can limit what can be sequenced. Different activities have increased levels of autonomy to account for unexpected conditions. For example, the rover is capable of autonomous navigation, which enables the rover to drive to locations without a prior knowledge of the terrain through which it will traverse.

Throughout the plan execution, the rover will produce and collect data products which record the results of its activities. It will also generate telemetry, which includes critical information about the state and health of the vehicle. All of this data is stored onboard awaiting transmission to Earth.

Steps (G): Downlink

The vast majority of the data received from the rover is sent via relay from one of the Mars orbiters. The rover must wait for the orbiter to fly overhead before it can transmit data. The amount of data that can be transferred to the orbiters varies with each window depending largely on the elevation of the orbiter in the sky as it passes over the rover. Data is prioritized by the operations team such that information critical to assessing the health of the vehicle and for planning the next sol's activities is sent earlier in the communication window.

Once the data is onboard the orbiter, it must wait for the orbiter to have a communication opportunity with Earth before the data can finally reach Earth and then get transferred to the operations team for analysis. As with uplink, technical problems may occur during downlink which can result in unexpected delays in data reaching the operations team.

The data becomes input to the next round of planning. It may be used to support the development of further activity, e.g. an interesting target for further study may be identified in a downlinked image, and it may result in new high-level objectives being formed, e.g. unexpected signatures in a spectral analysis may result in a new objective to characterize an area.

Case Study Results

Using the conceptual model in Figure 3 as a guide, we developed a data collection schema that includes intent, activities, constraints and data along with relations among these entities. We worked through each sol of the campaigns, sifting through the plans, acquired data and telemetry, and written reports from operations personnel to collect and organize data with respect to this schema. The data gathering process was a combination of manually reading through activity plans and operations reports along with scripts we developed to assist in the collection process. The scripts we developed included utilities to identify links between data products and the activities that used that data and utilities to collect data on predicted and actual vehicle resource allocations. The objective in gathering this data is to identify cases of low and high productivity during each campaign and to help identify the factors that contributed to each.

A full description of the results of the case study are beyond the scope of this paper. Following is a brief summary of the results. Table 1 presents a rough breakdown of the sol-by-sol activity conducted in each campaign in terms of how activity on each sol contributed toward campaign objectives. Sols labeled "Campaign" were those that directly contributed to the campaign objectives with remote sensing and/or drives. "Campaign Multi-Sol" sols are those in which significant activity was performed toward the campaign objectives as part of a multi-sol plan, either due to a weekend or restricted planning. The reason for calling these sols out separately is that the presence of the multi-sol plan limited the team's options for these sols. For example, had there not been a multi-sol plan, the team may have opted for to move up activity that was performed in a subsequent plan (e.g. a drive activity) which would have reduced the overall number of sols required to achieve the campaign objectives. The "Extra Drives" label denotes sols in which unexpected drives were required. The sols labeled "Deferred" were sols in which campaign objectives were unexpectedly deferred due to the need to respond to an issue identified during tactical plan development or in response to an event from received downlink data. For the Pahrump Hills campaign, the deferred sols were due to an unexpected interaction, identified during tactical planning, between Pahrump Hills objectives and high-priority observations of the comet Siding Springs making its closest approach to Mars. For Artist's Drive, the deferred sol was due to the need to repeat an activity from the previous sol, un-related to the Artist's Drive objectives, as received data showed the activity did not have the intended result. Sols labeled "Post-Drive Multi-Sol" were those sols in which the team was not able to achieve substantial campaign objectives due to lack of data following a drive during a multi-sol plan. Finally, Finally, "Runout" are sols of very low activity that used in cases the team had to create multi-sol plans but the tactical timeline capacity did not allow for sufficient time to develop activities for all sols of the plan.

Comparing the campaigns in Figure 1, we note that despite having different high-level objectives, the sol breakdown for Artist's Drive and Marias Pass appear to be the most similar. This is due to these campaigns having a similar number of restricted plans and both being conducted in similar, challenging terrain conditions.

Comparing the sol breakdown for Pahrump Hills with the other two campaigns shows that restricted sols have a major productivity impact for these types of campaigns. Table 2 shows the number of nominal vs. restricted shifts for each campaign. Pahrump Hills had a total of 9 tactical shifts of which 7 were during restricted periods of the mission. In contrast Artist's Drive and Marias Pass had more total shifts and few restricted shifts than Pahrump Hills.

The reason for the differences in number of restricted sols between Pahrump Hills and the other campaigns is largely luck of campaign timing. The Pahrump Hills Walkabout campaign happened to begin just as a restricted period was about to start. On the other hand, the Artist's Drive campaign began just after a restricted period had ended. Marias Pass began toward the end of a nominal period but solar conjunction began before the restricted period began. By the time conjunction was over and the team returned to operations, the restricted period had completed. Thus, it is only toward the end of the Marias Pass campaign that another restricted period impact operations.

The number of restricted sols is anticipated to increase for future missions as the current fleet of sun-synchronous orbiters are replaced with non-sun-synchronous orbiters. There are important science motivations for non-sun-synchronous orbiters, such as studying the Recurring Slope Lineae (RSL). However, such an orbit does not provide the consistent pattern of passes at the end of the rover's day. This will result in many sols in which the operations team does not have sufficient time to develop new plans in response to the latest rover data, thus increasing the number of restricted sols.

Table 2 also highlights the significance of terrain for these types of campaigns. Table 3 summarizes the traverses performed in each campaign. Note that the Artist's Drive traverse marked as "Drive Fault" was also limited by viewshed. Rather than double-count it, we counted it as "Drive Fault" and not "Viewshed Limited". The increased terrain occlusions encountered during the Artist's Drive campaign lead to a larger number of traverses being limited by viewshed than encountered during the Pahrump Hills Campaign. Although the terrain at Marias Pass was more challenging that Pahrump Hills, it had the same number of traverses limited by viewshed. This is likely because the Marias Pass campaign included returning the previously explored areas allowing the team to make use of terrain imagery collected on previous sols. The more challenging terrain of Artist's Drive and Marias Pass resulted in drive faults and the rover stability issues in the associated campaigns.

It is interesting to compare the Pahrump Hills and Marias Pass campaigns as they had similar high-level objectives but were conducted with different exploration strategies. Unlike the Pahrump Hills Walkabout, the Marias Pass campaign did not have an extensive strategic plan to direct activity. This was largely due to the geography of the Marias Pass valley. HiRISE imagery provided a high level overview of the region, with sufficient detail to indicate that the area contact a promising contact between the Stimson formation and

Sol Type	Pahrump Hills	Artist's Drive	Marias Pass
Campaign	6	9	10
Campaign Multi-Sol	2	4	4
Extra Drives	2	6	5
Post-Drive Multi-Sol	5	4	3
Deferred	3	1	0
Runout	1	0	2
Total Sols	19	24	24

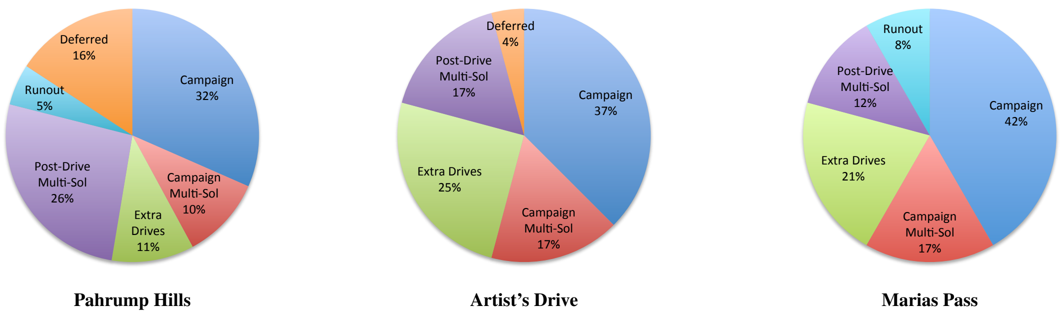


Table 1: Breakdown of sols for all campaigns.

Sol Type	Pahrump Hills	Artist's Drive	Marias Pass
Nominal Shifts	2	16	12
Restricted Shifts	9	4	4
Total Shifts	11	20	16

Table 2: Summary of shift types for all campaigns.

Sol Type	Pahrump Hills	Artist's Drive	Marias Pass
Nominal	5	6	3
Viewshed Limited	2	5	2
Drive Fault	0	1	2
Insufficient Stability	0	0	1
Total Traverses	7	12	8

Table 3: Summary of traverses for all campaigns.

Murray formation, but contained insufficient detail to form a strategic plan for exploring the location. Because the valley was elevated above the Artist's drive route the rover had been following, it was not possible to obtain the same type of Mastcam panorama that was available for planning the Pahrump Hills Walkabout.

Despite the absence of a detailed strategic plan for the Marias Pass campaign, the team was able to make quick tactical decisions and respond to new data as it arrived such as identifying drive routes and selecting key science targets. This can explain the why Table 1 shows a comparable number of campaign-oriented sols as Artist's Drive. In other words, it seems that the number of restricted shifts and terrain challenges was a bigger factor that the availability of a guiding strategic plan, given the teams ability to react.

It is also interesting to compare the walkabout approach employed at Pahrump Hills vs. the linear approach used at Marias Pass. Although the team intended to use a linear strategy at Marias Pass, then ended up backtracking to explore data collected near the Sol 992 location. There was additional backtracking in the sols that followed the end of our case study sol range. It was suggested by one of the scientists in our interviews that perhaps the Marias Pass campaign would have been overall more efficient had it employed a walkabout approach.

A full assessment of the benefits of these two exploration strategies is beyond the scope of a single case study. The interested reader is referred to Yingst et al. for additional discussion on this topic (Yingst et al. 2015). Their conclusion is that a walkabout approach can take more time to execute, but has the potential for achieving higher quality results. One of the objectives we have with this case study is to leverage what we have learned from these productivity challenges to identify flight and ground approaches that can reduce the overhead of employing a walkabout approach.

We performed a series of analyses on how the team allocated vehicle resources throughout each campaign. This included tracking of predicted and actual allocations of flight computer duration, energy and data volume. Figure 5 shows an example using the flight computer duration allocation during the Pahrump Hills campaign. Multi-sol plans are indicated with vertical black lines.

The analyses of resource allocations followed a similar pattern for each of the campaigns. The impact of multi-sol planning due to weekends and restricted sols had the largest impact in how effectively the team was able to allocate resources toward campaign activity. The analysis showed a general decrease in overall activity across multi-sol plans. This is likely due to limitations in how much activity can be developed during the tactical timeline. In addition, the team is limited in the types of activity that can be performed after a drive without ground-in-the-loop. The analysis also showed a significant decrease in the allocation of resources to campaign objectives following drives during multi-sol plans. This is because ground-in-the-loop is required to per-

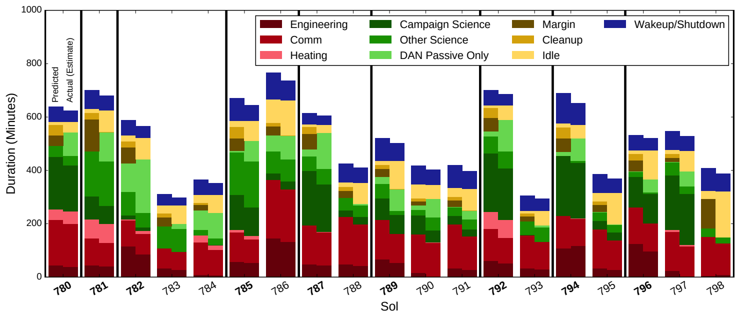


Figure 5: Allocation of flight computer duration for Pahrump Hills Walkabout campaign.

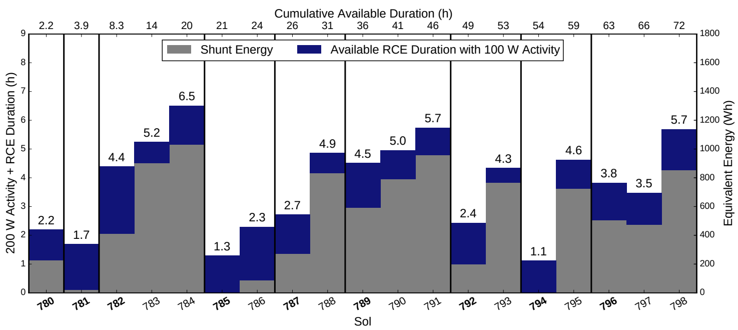


Figure 6: Estimate of extra duration availability for Pahrump Hills Walkabout campaign.

form the majority of the activities needed to accomplish the campaign objectives.

The resource analysis indicated that the team was not constrained by energy during this campaign. There was sufficient unused energy and sufficient non-productive vehicle awake time to support an estimated additional 72 hours of campaign-related activity over the span of the 19 sols for the Pahrump Hills campaign, as shown in Figure 6. Similar analysis estimated an additional 62 hours and 69 hours of campaign activity could have been performed during the Artist's Drive and Marias Pass campaigns, respectively.

As part of the case study, we were also interested in understanding the types of decisions that were made with ground-in-the-loop cycles. Following is a summary of common types of ground-in-the-loop decisions across the campaigns:

- Selecting targets for ChemCam, Mastcam and contact science: While distant imagery of terrain provided sufficient information to indicate the value of traversing to an area, the scientists required the higher quality imaging of the area, obtained when the rover arrives at the site, to select specific targets.
- Drive planning: Post-drive imagery is also used to provide the data necessary to plan the next traverse, including allowing the scientists to refine their selection of end-of-drive location and the engineering team to design a route for the rover to follow.
- Stability assessment for contact science: Prior to deploying the arm and performing contact science, the team must use data from the rover's current position to assess the vehicle's stability.
- Responding to problems in activity executions: It is a complicated mission and plan execution does not always go as expected. Unexpected terrain conditions can cause a drive to end early, resulting in the engineering team assessing the reasons for the problem and re-planning the drive. There are also cases where remote sensing observations do not work as expected. During the campaigns there was a case when imagery was re-acquired due to lighting issues with the first attempt, and cases where ChemCam observations of extremely small features needed to be re-acquired when previous attempts missed.

Addressing Surface Mission Productivity Challenges

The ultimate goal of this case study is to help identify changes to flight software and ground operations that will increase productivity for future missions. Based on the authors' operations experience and preliminary analysis of the results from the case study, we have developed a broad concept for the technologies we anticipate playing important roles in addressing these productivity challenges. The general theme of the changes we are considering is to move more knowledge of intent and more authority for decision making to the rover. Figure 7 provides an overview of the concept which we refer to as a Self-Reliant Rover.

Following is a summary of the key technologies in the concept and motivation for how we anticipate they will support increased productivity.

Goal Elaboration

We believe that an important step in increasing productivity of surface operations is changing the interface the operations team uses to interact with the rover. For the most part, the operations team interfaces with the vehicle with sequences which essentially provide detailed instructions on how the vehicle is to perform the team's desired activities. This approach is inefficient in a variety of ways. It is a time-consuming process to develop and validate the command sequences, especially in situations where the team must try to take into account uncertainty of the state that the rover will be in when the sequences are executed. Because the team does not know the actual state of available resources at the time of plan execution and because conservative resource models are often used, this approach tends to result in undersubscribing rover resources. In other words, the vehicle frequently has more time and energy to perform activities than predicted. Finally, this approach provides very limited ability to respond to unexpected events during execution.

We would like to move to an interface with the vehicle in which we tell the vehicle what tasks we want it to accomplish, rather than telling it how to accomplish tasks. This is important because how a task is accomplished may depend on the current state of the vehicle which is unknown to the operations team at plan development time.

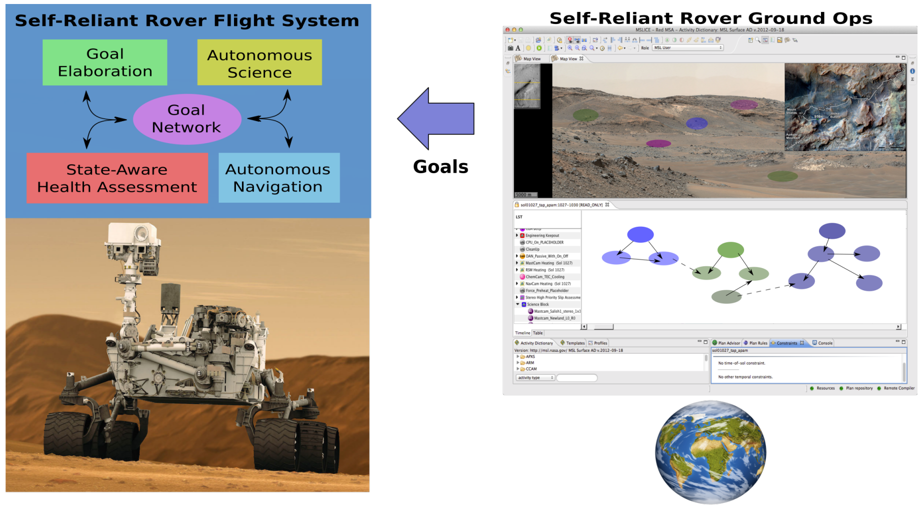


Figure 7: Key technologies for a Self-Reliant Rover.

Therefore, in the Self-Reliant Rover concept, the primary mode of interfacing with the vehicle is the specification of the team's goals. The rover will use goal elaboration to decide how to accomplish these goals given its current state. Further, the team can safely provide a set of goals that would potentially over-subscribe the available resources. The rover will use its up-to-date knowledge of its state along with ground-provided goal priorities to select a subset of goals that can be safely accomplished with available resources. The rover will still perform resource predictions to estimate resource availability for future activity, but these predictions will be continually updated with the latest vehicle state.

This approach, of course, requires more up-front effort in the flight software development process, to develop and validate the onboard planning models used by the rover. But we anticipate that it will result in a large payoff in the form of significant reductions in tactical development and validation of command products.

There exists a large body of work in planning and execution from which we will draw including (Chien et al. 2014; Worle and Lenzen 2013; Fratini et al. 2013; Rajan, Py, and Barreiro 2013; Ceballos et al. 2011; Dvorak, Amador, and Starbird 2008).

Autonomous Science

Many of the science activities performed by the rover require extensive knowledge of the state of the rover and its surroundings at the time the activities will be performed. The result is a significant reduction in science productivity when that information is not available. As discussed previously, this situation arises with restricted sols, weekends and holidays. In addition, it can occur with unfavorable downlink windows or due to unexpected downlink disruptions.

We are interested in exploring autonomous science capabilities to provide a means for scientists to express their intent to the vehicle without requiring up-to-date knowledge of the vehicle's state. The role of autonomous science is not to replace scientists, but to enable scientists to guide the collection of science data in situations in which they would otherwise be unable to do so. The AEGIS system, deployed on the MER and MSL rovers rovers, is an example of this approach to autonomous science (Estlin et al. 2012; Francis et al. 2015). AEGIS allows scientists to specify the types of targets they are interested in acquiring data on following rover drives. We are using the case study to help identify additional opportunities for onboard science to enable scientists to guide rover activity.

The autonomous science component will interact with the rest of the system by posting new goals into the goal network. Goal elaboration will select among these new goals based on available resources.

State-Aware Health Assessment

The traditional approach to health assessment in spacecraft has been to create fault monitors that detect pre-defined failure conditions, typically by detecting when measured values exceed some defined threshold. When a fault monitor is tripped, a pre-defined response is taken in an attempt to isolate the fault. This could involve precluding further use of an instrument or putting the entire spacecraft into a safe-mode, until ground can intervene.

In general, health assessment has been restricted to identifying and responding to pre-defined off-nominal behavior. We are interested in incorporating health assessment into the nominal operation of the vehicle. In our design, health assessment is an integral part of onboard evaluation of the performance of activity as it is executed. This feedback will enable the task executive to monitor ongoing activity, enabling it to make decisions about continuing the activity.

If problems arise, health assessment will enable the vehicle to identify faults and assess their impact in order to determine how to continue to achieve mission goals while ensuring vehicle safety. State-aware heath assessment will integrate with goal elaboration by updating states to reflect the health of various vehicle devices and subsystems. This in turn will pose new goals for longer-term fault response and impose constraints on how goals can be implemented. The system will maintain a high level of productivity in the face of faults by seeking alternative means of accomplishing impacted goals, if appropriate, or substituting alternative goals that previously did not fit within available resources.

Relevant work in this area from which the project will draw includes (Fesq et al. 2002; Robertson, Effinger, and Williams 2006; Hayden, Sweet, and Christa 2004; Mikaelian, Williams, and Sachenbacher 2005).

Autonomous Navigation

Autonomous navigation is one of the major areas in which rovers are provided intent and allowed to decide how to accomplish tasks (Maimone, Leger, and Biesiadecki 2007). However, when autonomous navigation is used, the operators typically set conservative constraints on the conditions under which the vehicle is allowed to continue autonomous navigation. For example, tight limits may be set on the amount of slip or yaw the rover is allowed to tolerate based on expectations the operators have of the terrain the rover will encounter. During restricted time periods of the mission, when the rover may go multiple sols without interaction with the ground, this conservative strategy can result in a significant reduction in productivity.

We will be exploring ways to make the scheduling of autonomous navigation plans more robust to unexpected terrain conditions. When terrain conditions deviate from expectations, the rover will assess if it is still safe to pursue its current route, if it should plan an alternate course, if it should halt and wait for ground interaction, or if it should give up on its current driving objective and choose a different goal. Decisions will be fed back to the rest of the system to enable coordination with the overall goals of the rover. For example, if the rover chooses to continue with the current path, an update on the time and energy required to complete the traverse will be made. This will be used to make an updated resource projection to see if this expenditure of resources is still consistent with the priorities of goals and required resource margins.

Ground Operations

In addition to changes to flight software, we are also investigating changes to ground operations that will enable future surface missions to address productivity challenges. The scope of these changes includes how the operations team communicates their intent to the vehicle and how command products are validated. Giving the vehicle authority on the goals it accomplishes and the ways in which it accomplishes those goals results in less certainty at planning time on what exactly the vehicle will be doing. This is a significant shift in how the operations team currently validates command products. We will explore ways to give operations personnel expectations on the behavior the vehicle will perform. We will also look for ways in which the ground team can constrain or guide the vehicle's behavior when desired.

Simplifying the interface with vehicle will reduce the time required to generate new plans. This will result in fewer restricted sols as the team will not require as much time to make uplink deadlines.

A major challenge in this work will be relaxing the reliance on up-to-date vehicle knowledge when developing command products. The goal is to make it natural for the team to not know the state the vehicle will be in when the command products are received, but still be able to express intent and guidance to the vehicle so that it can effectively carry out the teams' objectives.

Conclusions

We are in the early stages of a multi-year project to study and address productivity challenges of future surface missions. We have identified campaigns from the MSL mission for study which we believe will yield valuable information about the nature of surface mission productivity challenges. Based on preliminary analysis from the data collected we anticipate that the lessons from these case studies will help develop and mature our concepts for changes to flight and ground systems to address these challenges.

While the focus of our work is on Mars rover missions, we believe the concepts in the work will be applicable to a variety of in-situ explorers, including Venus, and Titan, as well as orbital missions, such as the Europa orbiter. These missions will also benefit from the ability to adapt and respond to the latest state of the spacecraft and its environment.

Acknowledgments

This research was conducted at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. This work was funded by the Jet Propulsion Laboratory Research and Technology Development program. We are extremely grateful to the MSL team for their support of this project. The generous assistance they provided in enabling access to MSL data, answering our many questions and supporting our interviews was invaluable to this study.

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