Management, Performance, and Productivity of the MSL Science Team

Introduction

Carrying out a complex planetary mission takes a lot of planning and management to achieve a successful mission. That is particularly so for the Mars Science Laboratory Mission, which attracted the creativity of a large national, international, and interdisciplinary group of scientists willing to devote a significant part of their careers to the joint effort over an extended period of time.

This chapter departs from the path of exploration of Gale crater by Curiosity to examine the planning of the science operations of Curiosity and her instruments, as well as the changes in plans made in the course of her operations. The planning to be analyzed in this chapter was recorded in an open-source peer-reviewed paper (and its supplement) published in Science Reports on July 25, 2012, two weeks before the Curiosity rover landed at Gale crater on Mars. (see box).

Original planning documents summarized in this chapter:

- Mars Science Laboratory Mission and Science Investigation by John P. Grotzinger et al.
- MSL Science Team Rules of the Road

Text is inserted in the summaries by this book’s author:

- Comments on applications of the plan
- Changes in the plan based on operational experience

The MSL Science Team is the group of scientists who will make the decisions to operate Curiosity and its tools to maximize the scientific results of the mission. They do this in cooperation with the JPL engineers who designed and tested Curiosity. The members of the MSL Science Team were mostly nominated by the Principle Scientists of the science instruments. Altogether, there are about 400 MSL Science Team members and Science Collaborators listed in Appendix: The MSL Science Team.

The Operations Plan Of the two documents listed in the box above, the first document is a training course text to explain what the science team needs to know about the Curiosity rover to participate in day-to-day planning groups. Formal guidelines for the management of the MSL Science Team during operations on the surface of Mars are in the Rules of the Road supplement. The MSL Science team is
also responsible for the release of data, interpretation of results, and communication of the results to the public and to the scientific community. The nearly 400 papers in peer-reviewed journals is an indicator of the magnificent performance of Curiosity, the MSL Science Team, and the engineers who worked to meet the challenges of the Mars surface environment.

The initial plans were based on the very successful operations of the Mars Exploration Rovers, Spirit and Opportunity and other earlier missions. After the first months of surface operations, the MSL Science Team realized that Curiosity, with its ten science instruments, was much more complex than the Mars Exploration Rovers. Changes were made in the methods of operations to increase the efficiency of making decisions. In part this was done to relieve stress on the Mars Science Team and in part to increase the efficiency of planning operations that take place over multiple sols associated with time and power intensive operations such as drilling and analysis of samples.

Summary, Comments, and Changes Comments on the success of specific parts of the plan and also on changes to the plan that needed to be made are inserted in the summaries of the planning paper and its supplement. To differentiate between the original documents and the comments and changes, the original documents are in italics, while this author’s comments and description of operational changes made in the course of the mission are in normal print. Additionally, to highlight transitions, a passage from the original documents will be introduced by the source in brackets: either [MSL Mission and Science Investigation] or [MSL Rules of the Road]. The author’s comments, summaries, and descriptions of operational changes will be introduced by [CB Summary], [CB Comment], or [CB Change].

The major changes are for the addition of an intermediate planning step, the Supratactical Process after early experience with surface operations. The process is described by “The MSL Supractactical Process” by Debarati Chattopadhyay et al. and a passage from the text will be introduced by [MSL Supratactical Process]. Finally, text taken from the Science Corner of the MSL mission’s webpage is introduced by [MSL Science Corner].

Summary of “MSL Mission and Science Investigation”

[CB Summary] The abstract of this tutorial paper gives an overview of the MSL, its rover, and its instruments. The body of the paper begins by summarizing the literature from 2000 to 2012, a period of orbital survey, describing the surface of Mars and the evidence for extensive flow of water in ancient times. Previous missions have established that while water in the form of ice exists near the poles, conditions today do not permit flowing water on the surface.

Yet the surface of Mars has been transformed by interactions with water through much of its history. That point had been made before Curiosity was launched. Curiosity and the MSL Science Team were to investigate how long flowing water and lakes have existed on Mars and what can be learned from examining the extensive sedimentary rocks with the complex array of instruments and tools. The MSL Science Team plans the route and actions of Curiosity and then consider the implications of the observations to learn about habitability, preservation (of signs of life), and variations in the environment of Mars.
Habitability and Preservation

[CB Summary] Two specific objectives for Curiosity’s instruments and the MSL Science Team were set by the pre-landing document: to determine the habitability of the environment for lifeforms in the past if not the present, and to investigate conditions that would (or would not) permit the preservation of evidence of such life if it had existed.

The necessary conditions for a habitable environment were set as the presence of liquid water, a source of carbon, and a source of energy to enable organic metabolisms.

Hazards to the preservation of biosignatures (an object, substance, or pattern requiring a life form to create) were also discussed. One difficulty is ambiguity: to be convincing, a biosignature must be distinct from any physical process. Also, complex structures of organic molecules can be degraded by radiation and particles of the solar wind, or by oxidizing environments. Finally, fossil structures formed by encasing or substitution of minerals in organic structures can be distorted or destroyed by changing environments.

[MSL Mission and Science Investigation] Thus MSL will be faced with a major challenge: both modern weathering processes (including radiation damage) and ancient diagenetic processes could conspire to inhibit the preservation of organic matter.

[CB Comment] The discussion in the pre-landing document on habitability was partly to define what habitability means and partly to manage expectations about instrumentation to detect past life. Shortly after the successful landing, besides confirming the previous understanding of water on Mars described above, Curiosity’s exploration provided an answer to “What’s next?” Early on, evidence was found of ancient water being neutral in pH, with the necessary evidence for elemental and mineral content needed to support life as we know it. As the exploration went on, it was understood that the view of “early Mars wet, later Mars dry” was too simple, and that there had to be a lengthy succession of wet and dry periods to establish the observed rock strata in Gale crater. To return to the pre-launch document’s expectation of what’s next, the concept of habitability of the environment was described as an objective for Curiosity and the MSL Science Team.

Many observations were made of ambiguous processes that are common in the presence of water, especially flowing or groundwater and are prolific at lower Mount Sharp. Crystal patterns in evaporate minerals have been seen that are similar to those left by bacterial colonies, for example. Positive evidence for the survival of somewhat complex hydrocarbons shielded from the solar wind by only a few milli-
meters of surface has been found, but a similar level of complexity has been found in interactions between rocks and water.

Studies of ancient Earth rocks tell us about the early evolution of the Earth’s surface and atmosphere, which not only led to the appearance of primitive life but also to the interactive relation between the biosphere, the atmosphere, and the surface of Earth. Even if a diligent search for signs of past life on Mars is unsuccessful, we will learn how a lifeless rocky planet develops and learn by comparison with Earth's history.

Water, even flowing water, is not sufficient for life; by observation, we have learned that even extremophiles—species that survive and propagate in conditions that provide minimal support, including unusually hot or cold temperatures—require a common array of elements, a supply of energy, and a limited range of temperature and a limited range of pH, a measure of acidic and basic water. Even the extremophile species, which can survive even in the pores of rocks, have their limits. They all are built partly with organic molecules, hydrocarbons. So the goal is to find evidence that there was (or prove that there was not) a condition where life could have been present. As it turned out, Curiosity's data showed that the evidence for the ancient environment when the examined rocks had been formed was within the range of parameters that could support the life we know on Earth.

Even on the crater floor, Curiosity found sufficient evidence for the Science Team to conclude that in ancient times, the Mars environment was habitable for microbial life as we know it on Earth. As she climbed Mount Sharp, evidence led to a similar consensus that the development of Mars was dynamic, with extreme variability in the extent of surface water. As evidence accumulates, it may be clear that such dynamic behavior was Mars-wide. On Earth, extreme climate change in the past has repeatedly led to the sudden extinction of a large fraction of species as well as the accelerated evolution of new species. Is it possible that climate changes on Mars were too rapid for the sustained presence of life? Or not stable enough to allow life to emerge?

Curiosity did find two possible biosignatures. It turned out that small fragments of organic compounds could be identified in samples only a few centimeters under the surface in an area where sulfur was present to help preserve them. However, inorganic genesis was possible. But the goal of finding a good place to look was achieved.

Further, a great deal was learned about how methane is generated on Mars. On Earth, most methane is generated by living organisms or by decay processes of living organisms. Detection of methane in the Mars atmosphere has been seen from Earth and from Martian satellites, but always for short intervals and never verified. In the first year on Mars, Curiosity’s sensitive instrument SAM sniffed the Mars atmosphere regularly and looked for methane, but did not sense levels of methane significantly above background level. A paper was written making that clear. Science media reported with a headline “No methane on Mars”, implying that previous sightings were false. The SAM instrument has a different mode than had not been used up to that time because it takes a lot of time and power. In that mode, nitrogen and water vapor are removed from each sample of the atmosphere and the remaining gas is tested for methane. The sensitivity is thus magnified, and in this way, methane became regularly detected above the background level of the new mode. The newly detected methane turned out to depend on seasonal variation. Sporadically, much large plumes of methane were also measured. These disappeared in a day or two, although models suggested they would persist longer. Recently, a very large plume was sensed not only by Curiosity but also by a Mars satellite passing near Gale crater. Finally, independent verification legitimized the past sporadic observations. So a common product of life on Earth has been observed on Mars. As in the case of fragments of organic molecules, methane can be generated by rocks with certain minerals and water, so the methane is not indisputable evidence of current or ancient life on Mars.

In summary, a great deal has been learned about how methane is generated on Mars in sporadic plumes of the gas. They are not only patterned by seasonal changes in surface temperature but also have been detected in both in situ and orbital instruments in similar places at the same time. Although the gas
disappears unexpectedly quickly, theories have been generated to explain this phenomenon (see the results section of Chap. 10).

The goal for Curiosity is not to detect life. It would be excellent if she did, but she does not have instruments that have a high probability of doing so. To detect past life, we would need to detect structures that could only have been made by living organisms or very complex hydrocarbons that could not be explained by inorganic processes. There are also arguments made that depend on biological sorting of isotopes and a property of molecules called chirality that distinguish life forms on Earth. At this time, if life has been present and pervasive on Mars, the way to have a reasonable chance of detecting it would be to return a diversity of samples to Earth for examination. That task would need to be done by other missions.

The realistic goal for Curiosity is to find Martian environments that would be likely to preserve life if it were there. Curiosity has contributed to that objective by finding pervasive evidence of processes that deposit calcium sulfate in veins in rock. Sulfur is said to be useful in preserving the complex hydrocarbons of life.

Environmental Records

[MSL Mission and Science Investigation] An essential point that Earth also teaches us is that in the search for signs of early life a null result is a not always a disappointment. Whatever may be lost in terms of insight into possible paleobiologic markers may be gained by an equally rich reward into the processes and history of early environmental evolution. Studies of Earth’s Precambrian sedimentary record have revealed secular changes in the oxidation state, acid-base chemistry, and precipitation sequence of minerals in the oceans and atmosphere (D.J. Des Marais, Isotopic evolution of the biogeochemical carbon cycle during the Precambrian. Rev. Mineral. Geochem. 43(1), 555–578 (2001). doi:10.2138/gsrmg.43.1.555; A.H. Knoll, The geological consequences of evolution. Geobiology 1(1), 3–14 (2003); R.M. Hazen, D. Papineau, W. Bleeker, R.T. Downs, J.M. Ferry, T.J. McCoy, D.A. Sverjensky, H. Yang, Mineral evolution. Am. Mineral. 93(11–12), 1693–1720 (2008). doi:10.2138/am.2008.2955). Knowledge of an equally informative environmental history may also be uncovered on Mars. The evolutionary path of surface environments on an Earth-like planet that lacked a biosphere would make a highly desirable comparison to Earth in order to understand better the unique aspects of our own planet’s history. These records of environmental history are also embedded within the same kinds of rocks and minerals that may also preserve the calling cards of biology. Therefore, an MSL mission that focuses on understanding mechanisms of potential biosignature preservation will also insure that we capture the record of early Martian environmental processes and history.

[CB Comment] The evolution of Earth’s environment has been profoundly influenced by the presence of life. Think of the banks of coal deposited by palm fronds for example, or the transformation of Earth’s atmosphere by algae and sunlight. If there was life on Mars, a comparison of the effects of that life on the environment with Earth’s own evolution would be enlightening. If there was no life on Mars, then the comparison would be what happens to a rocky planet with and without life. Either way, the record of the early environment is written in the sedimentary rocks, and it is up to Curiosity to help us read it. In fact, in the last few years after landing, the mission has been very fruitful in doing exactly that.

[MSL Mission and Science Investigation] This approach holds both the hope and promise of Mars Science Laboratory. The hope is that we may find some signal of a biologic process. The promise is that MSL will deliver fresh insight into the comparative environmental evolution of the early stages of Mars and Earth. That alone is a valuable prize. MSL was specifically designed for this purpose and the MSL team has a lot going for it: veterans of years of previous rover operations permeate the engineering and science teams; strategic decision making has already benefited from stunning high-resolution image
datasets obtained by the HiRISE camera on MRO, as applied to both drive-related terrain assessment at Gale crater and refinement of scientific objectives; and the rover itself will be the most capable robot ever sent to the surface of another planet.

[CB Summary] Sedimentary rocks tend to lay horizontally, each strata rising in the order of the time of their deposit. On Earth, fossils, which are structures of life, tend to be more complex with time as life evolves—an important characteristic of life—and are often found preserved in sedimentary rock. The orbital observations of sedimentary strata in Gale crater was one reason it was chosen as a target.

Management of the MSL Science Team

[CB Comment] The next section of the body (2.1 Mission Summary) was covered in the first chapter of this book. The following section (2.2 MSL Science Team) described the team’s structure and addressed the problems of establishing discipline in what would be the largest number of instruments and tools to be operated in the history of planetary exploration. The listing of scientists involved in the enterprise, including the analysis and documentation of the streams of data, the diversity of institutions they represent and the variety of roles they are assigned, can be found in Appendix: The MSL Science Team.

The “MSL Science Team Rules of the Road,” a supplement to the published paper, establishes the way in which the members of the MSL Science Team should work with each other, stating the three principles in the box below. These principles have been important in the past in resolving some of the conflicts that occur because of scarce resources and the need to make choices.

| Individuals can Meet Personal Goals While Cooperating to Maximize Achievement of Team Goals |
|---|
| **[MSL Science Team Rules of the Road]** |
| Meeting the scientific goals of the project will require coordinated interaction among all these participants (e.g., data sharing, interactive and interdisciplinary data analysis and interpretation, joint publications). Moreover, if this coordination is well conceived from the start, it can significantly influence the success of the project by encouraging opportunities for interdisciplinary results and discoveries and by maximizing the impact of the results of the project. While encouraging these interactions, the project must also encourage individual creativity and initiative and find ways to allow all members of the project to benefit appropriately from the scientific successes of the MSL. |

[CB Summary] The MSL Project Science Group (PSG) The need for an orderly process to make difficult decisions is greater with Curiosity than a less complex mission. This need is addressed in several ways. One step is to separate decisions between those that are strategic and those that are tactical. Some of the strategic decisions had been made in the choice to go to Gale crater and not one of the other three potential targets. Gale crater was targeted because it was deep but also had a central peak that was even higher than its rim. The orbital data indicated a variety of sedimentary rocks, which are good for recording changes in water flow and for preserving organic molecules. The strategic decisions are made by the MSL Project Science Group (PSG).

[MSL Mission and Scientific Investigation] The list of MSL PSG members is shown in Table 11.1.
### Table 11.1 Mars science laboratory project science group

| Name             | Role                        | Affiliation                      |
|------------------|-----------------------------|----------------------------------|
| John Grotzinger  | MSL project scientist       | California Institute of Technology|
| Michael Meyer    | Mars program scientist       | NASA Headquarters                |
| David Blake      | PI, CheMin                  | Ames Research Center             |
| Kenneth Edgett   | PI, MAHLI                   | Malin Space Science Systems      |
| Ralf Gellert     | PI, APXS                    | University of Guelph, Canada     |
| Javier Gómez-Elvira | PI, REMS                    | Centro de Astrobiologia/INTA, Spain|
| Donald Hassler   | PI, RAD                     | Southwest Research Institute     |
| Paul Mahaffy     | PI, SAM                     | Goddard Space Flight Center      |
| Michael Malin    | PI, MARDI and Mastcam       | Malin Space Science Systems      |
| Igor Mitrofanov  | PI, DAN                     | Space Research Institute, Russia  |
| Roger Wiens      | PI, ChemCam                 | Los Alamos National Laboratory   |

**[CB Summary] The PSG is co-chaired by the MSL Project Scientist and the Mars Program Scientist. The members are the 9 PIs of the 10 instruments (Michael Malin is PI of two instruments, MARDI and MastCam). The Charter of the PSG is defined in the body document by the paragraph in the following box:**

**Charter of the PSG**

**[MSL Mission and Scientific Investigation]**

*The primary function of the PSG is to advise the Project on optimization of mission science return and on resolution of issues involving science activities.*

*During landed operations, the PSG will have an important role providing strategic guidance to the Science Operations Working Group (that subset of MSL science team members on shift making tactical decisions on any given sol of the mission).*

*All MSL Science team members are expected to adhere to the Rules of the Road and any future updates approved by the PSG.*

**[CB Summary] Other Members of the MSL Science Team** To assist the PI, other members of the science team associated with the instrument are named by the PI, who may designate some of them Co-Investigator. There are also Science Collaborators named by the PI. JPL engineers who have been assigned to the interface of an instrument with Curiosity are designated as Science Investigators. There are other members of the Science Team that are called Associated Scientists. There are also Collaborator Scientists who are associated with members of the Science Team. The individuals assigned these diverse roles are listed with their roles in Appendix: The MSL Science Team.

The cooperative nature of the MSL Science Team, guided by the preceding section, was maintained throughout the exploration. It was not always easy because of the complex problems of interpretation that were presented by the nature of Mount Sharp and its complex history. At times, separate investigation teams were formed to develop competing explanations for unexpected observations. Also, downtime of specific instruments or engineering equipment complicated competition for resources like power, time in sunlight, and safe path availability. Fortunately, the long duration of the mission permitted discussion among many scientists over the publication cycle and even long campaigns to gather unplanned information. Sustained goodwill allowed resolution of many issues by compromise and acceptance of creative new ideas.
Gale Crater Field Site

The selection of Gale crater as a target site was very carefully formalized. It was a major factor in the success of the mission (Table 11.2).

[MSL Mission and Science Investigation] The PSG co-chairs (Project Scientist and Program Scientist), in consultation with the PIs determined that analysis of the landing sites would be aided by the involvement of the MSL Science Team, who would be intimately familiar with the instruments and objectives of the mission. These discussions became instrumental in defining the mission-relevant landing science criteria used by the broader Mars community in framing discussion of the candidate landing sites (Table 11.2).

It was decided to charter three PSG Working Groups, each operating under the auspices of the PSG co-chairs. The first of these was chartered to specifically look at the preservation potential of organic compounds and other biosignatures on Mars, as a function of different habitable environments thought to be present at the different landing sites as presented by the community. The second Working Group was chartered to lead comprehensive discussions and analysis of the final four landing sites. The third Working Group was charged with evaluating the traversability of the rover through sloping outcrops of the lower part of Mount Sharp. Where needed the Working Groups were inclusive of experts external to the Project and Science Team, so as to maximally enhance the return and objectivity of these efforts.

[CB Summary] The following is a description of the process of examining candidate landing sites and a listing of the attractive aspects of the Gale crater that resulted in its selection. In making decisions, members of the MSL science team referred more than once to setting a high priority to opportunities for investigation that were used in selection of Gale crater as a landing site.

Gale crater scored high on Diversity because of the distinct layers of different minerals; clays, sulfates, and cemented fractures as seen from orbit. In Context, it bordered two distinct regions, a highland area to the south and the dichotic Borealis Basin to the north. As for Habitability it had clear signs of water flowing over the edge of its crater and into the depth of the crater from both north and south. Because the floor of Gale crater is so far below the surrounding surfaces, the upward pressure of groundwater was strong below the crater floor. The possibility of lakes forming and then evaporating suggests a high preservation potential.

A mobility study promised a traversable path up the central mountain. Some paths could have turned out to be blocked, but alternate paths existed to allow reaching the key mineral layers.

Table 11.2 Four major mission relevant landing site science criteria [MSL Mission and Science Investigation]

| Criteria    | Description                                                                                                                                                                                                 |
|-------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Diversity   | A site with a variety of possible science objectives will ensure a greater chance for scientific success. Examples: multiple and differentiated science targets, multiple types of evidence (e.g., morphologic and geologic), variety in mineralogy or styles of stratigraphic expression |
| Context     | A site that can be placed in a larger, more regional context will ensure a greater depth of scientific understanding. The regional context provides constraints on past processes that led to the environments being examined locally. Locally derived results can, in turn, be extrapolated regionally or globally |
| Habitability| Sites with orbiter-derived evidence for habitable environments can be assessed to make specific predictions that will guide the exploration strategy for MSL. Particular high-priority geologic targets can be identified that can be accessed, interrogated, and interpreted by MSL |
| Preservation| Sites with a higher potential for preserving evidence for past habitable environments will ensure a greater chance of scientific success. Using terrestrial analogs, sites can be assessed for the particular physical and chemical conditions that retain mineralogic, chemical, or morphologic evidence |
[CB Comment] Visit to the Greenheugh Pediment  In March 2020, crossing the Greenheugh Pediment to reach the sulfate-bearing unit more quickly than following the planned path was considered. Despite the need for very high angles of tilt, the rover drivers have successfully brought Curiosity up on top of the lip of the pediment. The views are spectacular. Will they be able to proceed? As it turned out, after examination of a mosaic taken by the MastCam, Curiosity turned around and left the pediment. A mobility study was not encouraging, so Curiosity returned to the originally planned path. However, the visit to the pediment was scientifically productive with both remote and contact instruments, including a sample of a sandstone rock.

The next two sections of the published body document cover material on the rover and instruments that is addressed in earlier chapters of this book. Two figures not covered in early chapters of this book are presented here to represent the contents of these sections. Figure 11.1 shows the engineering components of the rover.

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Fig. 11.1 [MSL Mission and Science Investigation] Drawing of Curiosity indicating some of the major engineering components. The Robotic arm is stowed (folded up) in front of the rover and the Remote Sensing Mast is not extended. Open source, John P. Grotzinger et al., “Mars Science Laboratory Mission and Science Investigation”, Space Science Reviews, July 25, 2012
Figure 11.2 shows some of the tools of the rover that support instruments. Each of the instruments had at least one JPL engineer assigned to be a liaison contact with the Principal Investigator and the instrument team, representing the rover’s mechanical, electrical, thermal, and data interfaces with the instruments. After the landing, the rover liaison engineers assisted the instrument teams.

Entry, Descent, and Landing

Entry, descent, and landing activities occur within ~15 minutes prior to touchdown on Mars. MARDI acquires its data set from moments before heat shield separation through touchdown (<2 minutes) and a few seconds thereafter. For landing, MSL uses a propulsive descent “sky crane” to lower the tethered rover beneath it onto the Martian surface, setting its wheels directly on the ground. After rover landing, the connection with the descent stage is severed and the descent stage flies away to fall elsewhere, 150 m or more away from the rover. The rover will touch down in late southern winter (Ls = 150.7), between 14:50 and 15:02 Local Mean Solar Time on Mars, depending on the launch date.
Commissioning Phase

[MSL Mission and Science Investigation] The goal of the commissioning phase is to allow the mission to reach nominal science operations as quickly and safely as possible after touching down. Before this is possible, the rover operations team must characterize the health and behavior of the rover and instruments once interacting with the Martian environment. The first ~10 sols will be dominated by critical hardware deployments (e.g., the mast and mobility system), installing the flight software version used for surface operations, and spacecraft and payload checkout activities. After this initial characterization phase, mast-mounted and monitoring instruments may begin performing nominal science as operational time, power, and downlink data resources allow. The next few 10s of sols will involve checkouts and first-time uses of more advanced capabilities, such as the robotic arm and other sampling hardware. These activities will be coordinated with strategic science decisions such as whether to drive out of the region contaminated by the landing engines’ effluents, to fully enable contact science, to acquire a sample of soil, rock, or organic check material, or to focus on traversing toward other scientific targets.

[CB Comment] There was an interesting discussion over the first pictures from the hazcams to be downloaded. Some wanted a rear-facing hazard camera image to show stones first (Look! we are really on the ground!) and some wanted a front-facing hazard or NavCam to show Mount Sharp on the horizon (Wow!). At the actual landing, images were taken and sent to Earth front and back within minutes of touchdown. They were blurry and fuzzy with dust thrown up on the protective lens cover on the camera, which had not yet been removed. However, one picture was taken within seconds of the landing and showed an unsettled puff of dust that had been thrown up by a descent stage’s engine. The commissioning description continues below.

[MSL Mission and Science Investigation] These activities will be coordinated with strategic science decisions such as whether to drive out of the region contaminated by the landing engines’ effluents, to fully enable contact science, to acquire a sample of soil, rock, or organic check material, or to focus on traversing toward scientific targets.

[CB Comment] Even before landing, the MARDI camera was taking pictures during powered descent and storing them for transmission after landing. These were used, as planned, for determining the exact landing location within the target area. An early strategic activity for the PSG is to use the location of the landing to determine where to set the early targets for science activities. Four choices were discussed: go northeast to the delta from Peace Valley, go southeast to low-lying Yellowknife Bay, go south directly to Mount Sharp (crossing the Bagnold Dunes), or go southwest to pass the dunes and go through the Murray Buttes to Mount Sharp. The choice was to go to Yellowknife Bay and west around the dunes toward Mount Sharp. This turned out to be an excellent choice!

Surface Operations

[MSL Mission and Science Investigation] MSL’s primary mission spans one Mars year (669 sols or 687 Earth days) after touchdown. Science team activities will terminate six months after the end of the surface mission, whether it ends after one Mars year or after any number of extensions. Nominal science operations will occur throughout this period with a few exceptions—namely, the commissioning phase right after landing, a ~30-sol period of minimal operations centered on superior solar conjunction (18
April 2013), ~10 sols dedicated to software updates throughout the primary mission, and a few other maintenance activities.

MSL is intended to be a discovery-driven mission, with the science operations team retaining flexibility in how and when the various capabilities of the rover and payload are used to accomplish the overall scientific objectives. One major partition in the rover’s activities is between driving and “sampling,” where the latter represents a series of environmental, remote sensing, and contact science measurements may then lead to the acquisition, processing, and analysis of a sample of rock or soil in the analytical laboratories. The proximity of the specific touchdown location to targets of scientific interest within the landing ellipse, and to Mount Sharp itself, will influence the ratio of driving to sampling in the early mission.

Science activities on any particular sol are governed by a number of constraints that are measured or predicted for that sol, such as the Earth-Mars geometry and local time phasing, timing of telecom windows, downlink data volume capability, the time profile of energy available for science, and any thermally driven operational constraints or energy needs of the payload, rover subsystems necessary for payload operations (e.g., robotic arm actuators), or the rover. Science activities generally require more power than is available from the RTG and rely on drawing down the rover batteries. (This is also true for many engineering activities.) Battery capacity, RTG output, overnight battery recharge, and management of the state-of-charge over multiple sols, are all critical to science (and engineering) planning. The thermal limitations, including significant time and energy required to heat mast, arm, and mobility actuators, vary with both time of day and season. Most science activities will occur during daylight hours on Mars (Fig. 11.3). Throughout the mission the rover itself operates on Mars time. Commands for the sol’s activities are sent via the overnight orbiter telecom pass or direct-from-Earth at local mid-morning on Mars. The rover will complete its tactical science activities (i.e., those that influence planning for the next sol) in time to return the data via an orbiter telecom pass in the midafternoon. During the early portion of the mission, the operations team will synchronize its efforts to Mars time. Between midafternoon and the next morning on Mars, the science operations team on Earth will assess the downlink, plan the next sol’s activities, and prepare the commands. Data that are not essential for next-sol planning will be returned during the overnight orbiter telecom pass. This basic framework allows

![Fig. 11.3](mslmissionandscienceinvestigation.png) [MSL Mission and Science Investigation]. Mission schedule timelines for tactical operations carried out each sol. Top: 16-hour timeline carried out on Mars time (first 90 days after landing). Bottom: 8-hour timeline carried out on Earth time. SOWG is the Science Operations Working Group. Source: Open source, John P. Grotzinger et al., “Mars Science Laboratory Mission and Science Investigation”, Space Science Reviews, July 25, 2012.
approximately five hours for tactical science activities by the rover on Mars. Additional payload or rover operations can occur outside of this window if they are not critical to the next sol’s planning. Following the first 90 sols the operations team will revert to an Earth-based time schedule (Fig. 11.3).

During winter, the time available each sol for science operations may be reduced because of the need to use a greater share of energy to heat the rover actuators. Also, the largest actuators may not warm sufficiently until after the afternoon orbiter telecom pass. For this reason, winter operations may use every-other-sol commanding for more than 12 out of every 36 sols.

Mission Operations After Landing

[MSL Mission and Science Investigation] The first ~90 days of the mission is accomplished with all operations participants on site at JPL, with personnel working in shifts synchronized to Mars’ 24.6-h day and on duty around the clock, seven days a week. A description of how Mars Time operations worked for the Mars Exploration Rover mission is given in D.S. Bass, R.C. Wales, V.L. Shalin, Choosing Mars time: analysis of the Mars Exploration Rover experience, in IEEE Aerospace Conference, 5–12 March (2005), pp. 4174–4185, paper #1162. doi:10.1109/AERO.2005.1559722 and A.H. Mishkin, D. Limonadi, S.L. Laubach, D.S. Bass, Working the Martian night shift—the MER surface operations process. IEEE Robot. Autom. Mag. 13(2), 46–53 (2006). doi:10.1109/MRA.2006.1638015. Operating on Mars Time and extra staffing to cover the tactical uplink process will allow the extension of the tactical timeline from the normal 8 hours to a two-shift, 12 to 16 hour timeline (Fig. 11.3). A major objective of this period is to develop the capability to complete the tactical one-sol turnaround process in 8 hours or less, by increasing efficiency.

After a portion (or all) of this initial period, the flight team begins transitioning to operate via a distributed operations network, with the central hub at JPL. This enables the remote science teams to work from their home institutions for the long duration of the mission, interacting via internet and phone teleconferencing. The start time of the prime shift on Earth will track Mars time, sliding forward from 6 AM until it reaches 1 PM (Pacific). After this point, the downlink from Mars arrives too late in the day on Earth to allow commands to be generated before a reasonable end of shift. In these cases the ground cycle is postponed until the next available Earth shift. From a tactical standpoint, every other sol is lost during this period. However, science activities can be performed by the rover on every sol as long as they can be planned in advance and/or their results are not required immediately for future planning. This period of every-other-sol (or multiple-sol) commanding is expected to span about 12 sols of every 36-sol Earth-Mars phasing cycle. After the first six months of operations, the operations team will support 5 day per week tactical operations on Earth time, with multiple-sol rover plans prepared for weekends and holidays.

Strategic Planning

[The MSL Supratactical Planning Process] The Strategic planning process addresses the long-term aspects of planning, including development and testing of first-time activities, planning science campaigns, and long-term management of rover resources and constraints.

[CB Comment] As mentioned earlier, strategic planning is the responsibility of the Project Science Group (PSG). The group has a responsibility to plan the path of the rover in a way that the mission’s goals are reached efficiently and to ensure that the highest priority goals can be met. Consultation is necessary with mobility experts to assure that the chosen paths are trafficable or that alternate portions of the path are available. As the mission progresses and knowledge of the environment increases, the PSG revises the path to maximize scientific results.
The strategic plan for the conditioning phase after a successful landing had been pre-planned. When conditioning came to the mobility system, a strategic choice was needed. Now that the specific location was known within the target area, should Curiosity go on a long traverse westward to reach the planned ascent path to climb Mount Sharp, with its sequence of new mineral goals, or go southeast on a shorter path to Glenelg where there was a conjunction of three geologic units? They went toward Glenelg – a fortunate choice, because it led them to a streambed at Yellowknife Bay, where they achieved Goal I, sufficient evidence for ancient habitability there.

Starting along the path to Glenelg for mobility conditioning and leaving the area contaminated with exhaust from the rockets of the descent stage, they stopped at Rocknest to continue conditioning of the science and instruments. Curiosity took the first scoop sample there of Bradbury soil and passed it to SAM for analysis. By the end of the initial 90 days of operations as well as conditioning, the strategic and tactical processes had started working as planned, and significant science had been performed. The rover had covered 490 meters, the cameras had produced excellent images, and Curiosity had taken its first selfie. The new supratactacle process was evolving.

In Yellowknife Bay, the first major area to be explored, interesting features were seen in the cameras and visited. As a result, priorities changed as they came close to smaller but interesting features. The result was a confused path, with some features visited multiple times. As the mission progressed, it became a custom to do a walk-about when entering a new area; that is, to systematically cover the length and breadth of the area before selecting targets. This process was found to increase productive efficiency.

**Tactical Planning**

**[MSL Mission and Science Investigation]** The Tactical planning process is the truly reactive aspect of planning, responding to data received from the rover each sol. The timescale for Tactical Planning is typically one sol.

**[CB Summary]** Tactical decisions are the responsibility of the Science Operations Working Group (SOWG) each sol to plan the science activities for the next sol (or in some cases two or three sols). The SOWG chair is chosen by the members and is approved by the PSG. The chair of the SOWG reports issues that cannot be resolved by the group to the PSG.

**[MSL Science Corner]** Members of the SOWG represent the following themes

| Organic Geochemistry and Biosignatures | Chemical and isotopic composition of organic compounds in solid and gas samples and other elements/compounds of relevance to habitability Textural, chemical, mineralogical, and isotopic biosignatures |
|----------------------------------------|---------------------------------------------------------------------------------------------------------------------|
| Inorganic Geochemistry and Mineralogy  | Chemical, mineralogical, and isotopic composition of rocks and soils                                                  |
| Geology                                | Bedrock geology, geomorphology, and stratigraphy Rock and soil textures Rock and soil physical properties             |
| Atmosphere and Environment             | Meteorology and climate Distribution and dynamics of water and dust Solar, UV, and high-energy radiation Atmospheric chemical and isotopic composition |
There is a thermal representative to monitor that the instruments are in their temperature ranges, an uplink manager, and a downlink manager that assure that the data requirements are within the allowance.

[CB Comment] Early during the Rocknest and Yellowknife Bay Explorations, the SOWG realized that sampling by scooping or drilling and waiting for the results of SAM analysis was taking longer than expected. These activities used a great deal of power and time, especially if the results of SAM analysis were reviewed before starting the next sample. As the mission progressed and operations become more complex, especially as unexpected environmental hazards damaged the wheels, it became difficult for an SOWG meeting to plan for operations that would take two or three sols to carry out, depending on the type of activity.

[CB Change] Since the Supratactical Planning Process has been implemented, the SOWG has been guided by a skeleton plan for multi-sol activities from the newly created Supratactical Planning Process.

The Tactical Planning Process

[CB Summary] Daily SOWG Meeting Schedule Initially, for the first 90 sols after landing, when all active planning personnel were physically at JPL, the original Tactical Process meeting took 16 hours. This was also the time between the download of data from the end of a sol to the start of Curiosity’s day for uploading the commands for the next sol. The time available to get yesteryear’s report and plan the operations for tomorrow’s sol was equal to the time needed to create the plan. This required the work time to slide with Mars time, starting 39 minutes later each Earth day. Obviously, locking the work time to Mars time caused great stress on the members, considering both health and family, especially on weekends.

[CB Change] Part of the problem was that harmonizing the long-range Strategic Planning with the short-range Tactical Planning was taking time from the Tactical Process. Inserting the Supratactical Process with additional personnel removed the burden of harmonization from the Tactical Process, ultimately allowing them to complete their work in 8 hours. The PSG changed the schedule, allowing them to meet at the same time for a number of sols and then move to another stable time. It also allowed for planning, on occasion, of 2 or sometimes 3 sols, additionally relieving the problem.

[CB Comment] Of course, with so many Solar System scientists in the MSL Science Team, a few will want to see an eclipse of the sun, even if it is only partial (see Fig. 11.4).

Sol Types One of the actions of the Tactical Process is to designate, according to the skeleton plan, the type of the next sol. The sol type varies in the instruments and rover tools that are used to achieve the results of the next sol. The chart in Fig. 11.5 (from the original published document) describes the sol types. The sol types for a series of sols may be specified in the skeletal plan provided by the Supratactical Working Group to the Science Operations Working Group.

The purpose of defining sol types is to provide focus to the activities that can be carried out efficiently in a given sol. For example, Traverse to a new location will require a drive. The longer the drive, the less power will be available for other functions. There are two combination sol types, Dilution/Sampling and Analysis/Observation tray. The dilution, sampling, and analysis functions use a lot of time and power. The observation tray uses a lot of time.
**Fig. 11.4** A subset of the Curiosity tactical planning team (SOWG) took a short break from planning during sol 1793 to view the solar eclipse of August 21, 2017 from the roof of building 264 at JPL. Notice that there are fewer people than Curiosity has instruments and tools. Additional members of the SOWG were in contact electronically from other locations. (Image courtesy of NASA/JPL-Caltech)

**Fig. 11.5** [MSL Mission and Science Investigation] This is a chart of instrument activities on MSL soil types. The left column of this chart shows the types of sol. The remaining columns are the scientific activity that may be used for that type of sol. Open source, John P. Grotzinger et al., “Mars Science Laboratory Mission and Science Investigation”, Space Science Reviews, July 25, 2012
Preparation activities are needed at the beginning of each of these activities, and specific observations and data downlink are needed at the end. Dilution is a process of removing contamination. Curiosity processed and analyzed five scoop samples to flush out residual organics. Then the first two drill samples were taken close together to check for different levels of contamination. For Contact sol types that use the arm and turret to position instruments, only one instrument can be used at a time.

With the exception of the sampling, analysis, traverse for long distance, and imaging for large mosaics, activities can often be carried out within one sol. But for these important activities, a new human group with a longer view than one to three sols is needed to orchestrate the tactical decisions.

**Supratactical Planning Process**

**[The MSL Supratactical Planning Process]** The Supratactical planning process bridges the gap between Strategic planning and Tactical planning, and incorporates certain aspects of predictive as well as reactive planning.

**[CB Summary]** The multi-sol planning problem of the SOWG was seen as stemming from the two-step decision-making method—strategic and tactical—that did not allow for multiple sol sequences to be planned without waiting for the results from the first sol in the sequence. The need for this was the increased complexity of Curiosity’s science instruments, particularly in regard to the time and power requirements for the sampling process and the SAM suite of instruments.

The solution was to change the planning process to insert an intermediate planning step called the Supratactical Planning Process between the strategic and tactical levels, with a new team of members selected from personnel that had been involved in development of the rover’s power system and instrument interfaces. An example of this team’s role was holding back power requirements for one sol to charge the battery so there would be more power available for the next sol. This process allows for sustained activity for many sols and peak power (MMRTG plus battery) for intermittent sols.

This modified the original decision process that had been based on experience with the Mars Exploration Rover mission. The original two-step process was not sufficient for planning of the more complex Curiosity rover, with 10 science instruments competing for power, time in sunshine, arm and turret, etc. A paper on the new MSL Supratactical Planning Process was delivered by JPL’s Debarati Chattopadhyay et al. at the 13th International Conference on Space Operations. The three-step planning process is shown in Fig. 11.6.

**[CB Comment]** The paper “MSL Superatactactal Planning Process” mentioned above concluded:

**[The MSL Supratactical Planning Process]**

*Given the lessons learned from MSL, it is likely that future missions which have complex payloads, and interactions with a planetary surface or other rapidly changing environment resulting in a time-constrained tactical timeline could benefit from a Supratactical process. It is worth considering early in the mission development whether this type of process could add value to the mission.*
Estimated Mission Performance at Gale Crater

[CB Summary] How do you measure performance of a planetary mission? Before landing, the MSL Project Group decided to select as measures of performance the distance traveled by Curiosity and the number of samples taken and analyzed in the first Mars year after landing. Of course, it was really knowledge gained that mattered. Both the questions answered plus the new questions raised will outlive the mission itself. Nevertheless, performance figures could be estimated before launch as measures of design success or failure. 18-km distance traversed and 11 samples taken in one Mars year (668 sols) were deemed best-case measures that assumed that there were no interruptions due to environmental problems or equipment failures resulting in down time.

The MSL survived launch, cruise to Mars, the entry, descent, and landing in the planned target area, and on-schedule communication with the orbital escort spacecraft. After one Mars year (about two Earth years) in the Martian environment, it was still traveling and still had full capability for sampling and analysis. Curiosity had traveled 8 km and had taken 5 scoop samples and 3 drill samples by sol 668.
In terms of the selected performance numbers, things did not look too good, except that we had a healthy Curiosity. Now, after four Mars years (and still going), we have traveled more than 20 km and taken over 30 samples. So, Curiosity is getting the job done, even if it is taking longer than originally estimated. The increase in later productivity is probably linked to the introduction of the Supratactical Planning Process near the end of the first Mars year. Another factor may have been the systematic use of a walk-about survey when entering a new area.

[CB Change] In terms of answering questions, Curiosity is a tremendous success. In only half of a Mars year, she has unquestionably relayed images and sampled minerals that resolved the central question of its mission: has Mars ever been habitable? The answer is an unqualified yes. Mars once had flowing water with a nearly neutral pH level. The mudstone rocks had the elements needed for life as we know it and the molecular composition of the rocks showed that energy sources were present. Earth life could survive now, if water was supplied and shelter provided for protection from the Mars atmosphere and the solar wind. Perchlorate ions in the soil and atmosphere are toxic to some organisms and food for others. Other answers have come as well, described in the Results section of each chapter. Other questions have been raised, some of which have also been answered by the Mars Science Laboratory.

Scientific Papers Published by the MSL Science Team Members Another measure of productivity is the number of peer-reviewed published papers in professional journals. The MSL project has kept such records and the number per year (after the year of landing) and the cumulative number are shown in Fig. 11.7.

![Fig. 11.7 Peer-reviewed published papers (black) from the MSL Science Team by year of publication and the cumulative number of papers (blue). Data source: NASA web page: https://mars.nasa.gov/internal_resources/840/. Graph by Charles J. Byrne](https://mars.nasa.gov/internal_resources/840/)
Planetary Protection

[CB Summary] The following is a summary of the extensive steps taken to comply with international standards to avoid contamination of Mars by the Mars Science Laboratory.

In the study of whether Mars has had environments conducive to life, precautions must be taken to avoid introduction of microbes from Earth by robotic spacecraft. The MSL complies with an international treaty and with NASA regulations. The following statement is a more detailed description of the methods taken to avoid contamination by Curiosity and supporting MSL units that reached the Martian surface:

[MSL Mission and Science Investigation] NASA’s primary strategy for preventing contamination of Mars with Earth organisms is to be sure that all hardware going to the planet is biologically clean. The Mars Science Laboratory mission is allowed to carry up to 500,000 bacterial spores on the entire flight system, specifically including the equipment discarded during entry, descent and landing.

The standard of cleanliness is even stricter for portions of the rover’s sample-acquisition hardware that will contact the Martian subsurface or the interior of rocks. While these components are baked to sterilize their surfaces using the same techniques as other hardware, special care is taken to prevent possible recontamination that can occur even in a cleanroom.

The Mars Science Laboratory is also complying with a requirement to avoid going to any site on Mars known to have water or water-ice within one meter of the surface. This is a precaution against any landing-day accident that could introduce hardware not fully sterilized by dry heat into an environment where heat from the mission’s radioisotope thermoelectric generator and a Martian water source could provide conditions favorable for microbes from Earth to grow on Mars.

[CB Comment] Since 2013, after Curiosity’s investigation of Yellowknife Bay was completed and its results understood, it became clear that extremophile bacteria could have a chance of survival under the surface, protected from the solar wind, where liquid water might be present. In light of these findings, the need for planetary protection persists for Mars.

There have been problems experienced with the sterility of Curiosity’s drill bits and wheels. In both cases, remedial action was taken.

Summary of the MSL Mission and Science Investigation

The Mars Science Laboratory Mission represents an ambitious step forward in the exploration of the planet. The interplay of sequential and overlapping orbiter and rover missions has dramatically improved our understanding of the history of Mars surface environments, including those that may have been habitable by microorganisms, had life evolved on Mars. The data from Curiosity’s ten scientific instruments has been entered, after calibration, into NASA’s Planetary Data System.

The rest of this chapter summarizes and discusses the MSL Science Team Rules of the Road.
The MSL Science Team Rules of the Road

[CB Summary] The management structure of the Mars Science Laboratory Science Team was established by a document entitled “Mars Science Laboratory Science Team Rules of the Road,” a supplement to the published “MSL Mission and Science Investigation,” the subject of this chapter so far. The members of the MSL Science Team were listed in the MSL Rules of the Road and are also listed in Appendix: the MSL Science Team of this book. It is an impressive roster of about 400 experts in planetary science and instrumentation from a diverse set of institutions, both American and International. Like the body document, the Rules of the Road supplement was published on July 25, 2012, just a few weeks before the landing of Curiosity.

The document was published as a supplement to “Mars Science Laboratory Mission and Science Investigation,” an article in *Space Science Review*, July 25, 2012. It is an historical document, recording what the leaders of the MSL were thinking about management of surface operations just before the landing. Topics included were making operations decisions to optimize science results, data sharing among members of the science team, and publication ethics. The document was prepared by John Grotzinger, MSL Project Scientist, Ashwin Vasavada, Deputy Project Scientist, Joy Crisp, Deputy Project Scientist, and Michael Meyer, MSL Program Scientist. Nine Principal Investigators, were listed as “concurred by.”

Professor Grotzinger has kindly given this author permission to include the supplement containing the MSL Science Team Rules of the Road in this book. Parts of the rules are modified in order to reflect changes that took place during the mission, specifically the creation of the Supratactical Planning Process to manage the complexity of surface operations of the many science instruments of the rover.

The Rules of the Road describes a management team called the Program Science Group (PSG): members are John Grotzinger, the Chief Scientist, Michael Meyer, the Program Manager, the Principal Investigators, with others as needed. In January, 2015, Aswin Vasavada succeeded John Grotzinger.

Note that the two management documents were published about two weeks before Curiosity landed in Gale Crater on August 6, 2012, so the personnel listed in Appendix A were organized before touchdown (they were selected in the previous November about the time of launch), although the way they would work together was still being finalized. In fact, the mode of operations changed as the mission went on and experience with the most complicated mission to date was gained.

The Rules of the Road addressed two topics. One was how the MSL Science Team worked together and with the PSG during mission operations. The other, as results were achieved, concerned data privileges and publication ethics.

Operations decisions were divided between strategic and tactical issues. Strategic plans, like broad areas to explore and planned routes, are the responsibility of the PSG. Tactical plans, like how to maximize science results in an interesting area, are the responsibility of the Science Operations Working Group (SOWG). Each such group has a theme, voluntary members, and a chair. The PSG provides oversight to the working groups and assures that their decisions support the strategic plans.

As described above in this chapter, the Supratactical Process, with additional members, was added to deal with multi-sol coordination and allow the Tactical Process to concentrate on the next sol, in consideration of the results of the previous sol.

The data privilege polices and publication policies were substantially unchanged in the course of the mission so far.
Data Privileges Policies

[CB Summary] Data sharing managed by the MSL project, consistent with the Mars Exploration Program Data Management Plan, is of four types:

- Data sharing within the MSL project
- Data release to the general public
- Release of data and discussion of interpretations through the media (print/radio/TV/film)
- Data sharing with the science community

[MSL Science Team Rules of the Road] Within the MSL, each investigation should produce processed data products at their home institution or at JPL and provide them fully to the Ground Data System (GDS) to be available to the entire science team and to the engineering operations teams. In principle, this also applies to engineering data being available to the science team. This is important in guiding the Strategic, Supratactical, and Tactical planning processes so that each sol has the benefit of the results of the previous sol’s activities in order to optimize the scientific return of each sol. It is the responsibility of Principle Investigators or Participating Scientists to distribute data and data products in a timely fashion to their collaborators. It is expected that data will evolve from raw, to provisionally analyzed, to validated and to archivable states. All data products will be made available to any MSL team member or collaborator.

As a general rule, any MSL data products (including calibration data) will be made available to any MSL Team Member or Collaborator.

Data Release to the General Public In order to engage the public, the MSL Science Team or NASA (through the MSL project office) may release interesting data or data products from each of the science instruments in a timely fashion. Unless such information has not been previously released publicly by NASA or MSL, it may only be released with the approval of the PSG or through a PSG defined process. The PIs will have the primary responsibility for representing and coordinating their teams regarding such releases. These approvals also apply to websites maintained by team members, collaborators and their institutions, as well as blogs to other web sites.

All images downloaded from the two Navcams and the four Hazcams will be posted as rapidly as possible on a world Wide Web site hosted by JPL. Release of these images to the web will not be delayed intentionally and will not require review or approval by anyone.

[CB Comment] Image Data Transparency This policy has not only been honored but applied to the science cameras as well. It has helped project an image of transparency for NASA. The raw images have been archived and are easily available by sol or date on a webpage that can be found by a search for Mars MSL Raw.

[MSL Science Team Rules of the Road] Release of Data and Discussion of Interpretation Through the Media (Print/Radio/TB/Film) Interviews of members of the MSL Science Team should be coordinated with the JPL Media Relations Office and approved by the PSG. Requests for approval are expected to
be coordinated by the PIs, leaving several days for the approval. The PSG will work with JPL Media Relations to develop guidelines for different levels of public exposure, different levels of media training of the members, information about mission status, and special situations.

Each PI and each MSL Science Team memberi may release data from their home institution’s media relations office, provided the PSG approval and JPL Media relations coordination has been completed. An important issue in releasing information is to share credit appropriately within and across PI-led teams and the PSG will take particular care in considering this issue.

Data Sharing With the Science Community By NASA policy, investigators do not have exclusive use of the data taken during their investigation for any proprietary period. However, it is recognized in the Announcement Opportunity for the MSL project that some time is required, not to exceed six months, for data products to be generated and validated. Therefore, PIs are responsible for delivery to the Planetary Data System (PDS) of Level 0 and Level 1 data (to PDS standards) no more than six months after receipt on Earth.

The documentation delivered to the PDS shall describe the higher-level products must include a complete description of the methods of generating them. A reasonably skilled end user should be able to understand the methods and reproduce the scientific results derived from the data products.

Before delivery to the PDS, no data products shall be released to the science community other than results contained in scientific publications or associated supplementary data unless the products were released to the general public as described in this Rules of the Road document or the MSL Archive Generation, Validation and Transfer Plan. This requirement must be accepted by all members of the MSL Science Team in order to protect confidentiality and openness within the team.

An exception to this rule is that relevant results may be released to selected members of the community if an unexpected situation arises and there are no existing team members or collaborators with adequate expertise are available. All such releases must be approved by the MSL project scientist after consultation with the relevant PIs or the entire PSG.

Publications

[CB Summary] It was anticipated that there would be a steady stream of results from the array of instruments and cameras that would generate scientific papers, abstracts, and talks. The responsibility for coordinating these releases lies with the PSG. The Rules of the Road discusses the role of the PSG, authorship guidelines, anticipated publications, presentations at scientific conferences, informal talks, and follow-on science. Given the large number of scientific participants, the integrated nature of most of the anticipated results (i.e., most publications will involve team members and collaborators associated with multiple PI-led investigations), and the importance that most scientists attach to obtaining recognition for their work, it is anticipated that the twin goals of effective communication and achieving equity may require delicate balance and coordination of the team and collaborators. The following is a short summary of the very detailed content of the Rules of the Road on this important topic. Reference should be made to a current version of the Rules of the Road or the Science Corner on the MSL mission webpage.
The Role of the PSG  The coordination and implementation of the publication policy will be the responsibility of the PSG, including

- What papers will be written
- Authorship
- Which results will be put in the papers
- Coordination of the results of the project to the scientific community
- Balancing issues of equity and quality among the many participants in the project
- Allocation of credit for obtaining and processing data
- Allocation of credit for creativity and development of interpretations and hypotheses
- Allocation of credit for scientific leadership within the project
- Respect divergent interpretations
- Encourage the publication of minority viewpoints and multiple interpretations of the same observations
- Meet regularly to monitor the progress of manuscripts in preparation and discuss plans for future publications.

PSG Decision Process  It is expected that most decisions will be made by consensus. If a decision is not supported by a consensus, the project scientist shall attempt to craft a compromise that the PSG accepts. If that is not successful, the co-chairs shall make a decision. If one of the co-chairs has a personal stake in the outcome of the decision, the other co-chair shall make it.

Authorship Guidelines  Complex rules for authorship prioritize team member, collaborators, and other members of the scientific community in that order, providing they make a substantive contribution to the writing and/or the research reported in the paper.

[CB Comment]  In general, the PSG has performed well, as the list of nearly 400 publications with many co-authors each attests. In reviewing the long list of responsibilities above, they were presented with certain challenges. The largest and longest lasting issue was how to handle the controversy concerning alluvial or aeolian transport and deposit of sediment. After exploration of the Pahrump Hills, opinion was turning toward lake deposits. After Marias Pass, aeolian transport gathered supporters for certain units that were newly observed there. In the summer of 2017, each of the proposals was supported by alternate peer-reviewed papers of many authors, approved by the PSG. A compromise proposal was published by 2018 with a revolutionary proposal of the Siccar Point Group that postulated the alluvial Murray Formation was deposited on the shores of Gale Lake as its surface rose in a series of wet periods. Then the younger aeolian Stimson Formation was deposited as the lake level alternately fell and rose in cycles, ultimately falling, as the climate dried and the sediment lithified. This compromise paper was authored by both groups.

The mission’s scope was redirected to the extensive “Dunes Campaign” to explore aeolian processes as they continue to the present.

The Rules of the Road asserts authority of the PSG for six months after the end of MSL’s exploration of Gale crater. The end may come with some random, fatal event, and also could come not with a bang but with a whimper, such as a gradual decline of power. In that case, high-power instruments will be turned off first and gradually, PIs will withdraw. In that event, it is likely that the Rules of the Road will be modified.
Summary of MSL Science Team Operations

After four Mars years and longer than seven Earth years on Mars, the Curiosity rover has been outstandingly successful in expanding our understanding of Mars as well as of Gale crater. The design, operations, and performance of the Science Team in operations, analysis of results, and publication have justified its ambitious goals. New goals are likely to be realized in the remaining years of operation.

The MSL Mission and Science Investigation, and its supplement, the MSL Science Team Rules of the Road, served well to prepare the members of the MSL Science Team to carry out their responsibilities, as did the ongoing guidance.

[CB Change] Coronavirus Pandemic  The 90-day period when the operations teams all met at JPL ended in December, 2012, so in 2013, many members returned to their normal institutions. Since then, the operations teams worked with many members linked electronically. Since mid-March, 2020, all JPL Curiosity operations team members teleworked, after a short period for some hardware and software modifications that were needed to accomplish this, especially for navigation.

All JPL workers that can do so are now teleworking, including for strategic, supratactical, and tactical operations. The only activities that require presence at JPL are performed with recommended precautions. An example of such an activity that might be associated with the MSL Curiosity mission would be testing of a workaround procedure to overcome a problem at Mars.