Mars Science Laboratory Participating Scientists Program Proposal Information Package

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The MSL Project Science Office

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Replies will be returned to the requestors. In addition, all of the questions and answers will be posted on the NSPIRES web site or a link from that site, preserving the anonymity of persons who submit the questions. All proposers should monitor this site, to benefit from the information.

DISCLAIMER: Although every effort will be made to implement the designs and plans described in this package, budgetary, programmatic, schedule, or technical issues may result in changes in these plans.

1 Table of Contents

2 Overview

2.1 Document Overview

This Proposal Information Package (PIP) document describes the relevant aspects of the Mars Science Laboratory (MSL) Project, in support of the NASA Research Announcement for MSL Participating Scientists.

This Proposal Information Package includes an overview of the MSL Project, description of the rover, rover instruments and science investigations, mission planning, and science operations. Appendix A is a draft version of the MSL Archive Generation, Validation, and Transfer Plan. Appendix B is the current MSL Science Team Rules of the Road document. Appendix C is the current NASA Mars Exploration Program data management plan.

2.2 MSL Mission Summary

The Mars Science Laboratory Mission will explore and quantitatively assess the habitability and environmental history of a local region on Mars. The mission has the primary objective of placing a mobile science laboratory on the surface of Mars to assess the biological potential of the landing site, characterize the geology of the landing region, investigate planetary processes that influence habitability, and characterize the broad spectrum of surface radiation. The MSL Project aims to achieve this objective in a manner that will offer the excitement and wonder of space exploration to the public. Figure 1 shows the rover, with its instrument arm deployed.

The mission will be launched on an Atlas V 541 from Cape Canaveral Air Force Station in Florida. The baseline plan is for the launch to occur sometime between 25 November 2011 and 18 December 2011, with an arrival date at Mars between 6 August 2012 and 20 August 2012. The primary science mission is one Mars year (669 Mars sols or 687 Earth days).

The major systems of the MSL Project consist of a single flight segment including payloads and the Multi-Mission Radioisotope Thermoelectric Generator (MMRTG), a launch vehicle, and the mission system/ground data system. The flight system consists of an Earth-Mars cruise spacecraft, an Entry, Descent, and Landing (EDL) system, and a mobile science rover with an integrated instrument package. The primary communication path for downlink is relay through the Mars Reconnaissance Orbiter (MRO). The primary path for uplink to the rover is Direct-from-Earth (DFE). The secondary paths for downlink are Direct-to-Earth and relay through the Mars Odyssey orbiter.

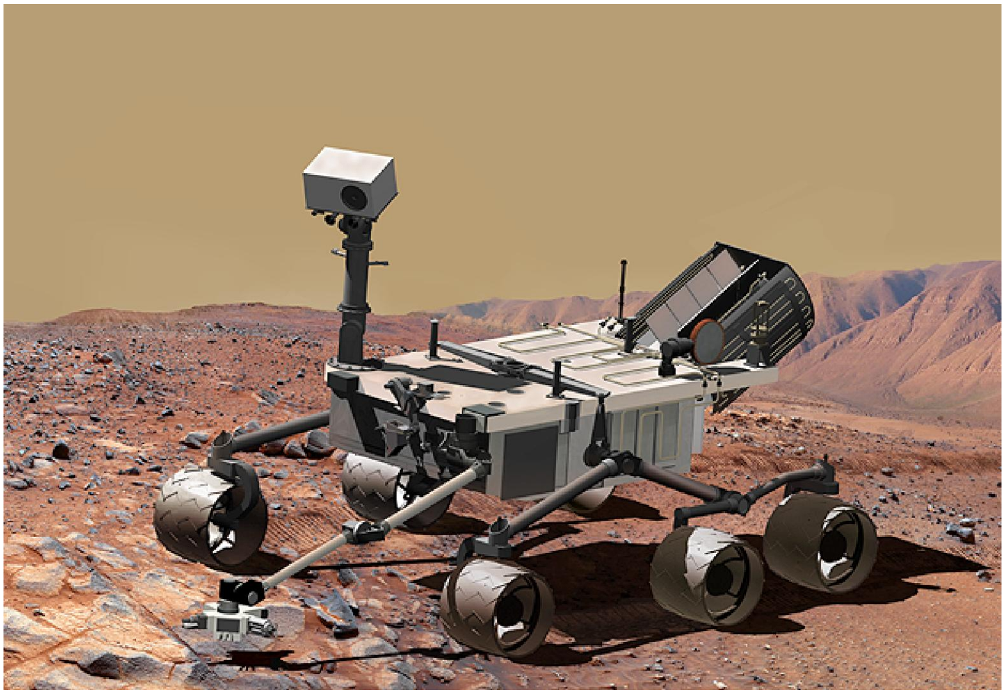

Figure 1. Artist's rendition of the MSL rover on Mars, with the robotic arm extended.

2.3 MSL Science Objectives

The Mars Science Laboratory will begin surface operations soon after landing in the summer of 2012 and continue for at least one Mars year (approximately two Earth years). The overall scientific goal of the mission is to explore and quantitatively assess a local region on Mars' surface as a potential habitat for life, past or present. The MSL rover is designed to carry ten scientific instruments and a sample acquisition, processing, and distribution system. The various payload elements will work together to detect and study potential sampling targets with remote and in situ measurements; to acquire samples of rock, soil, and atmosphere and analyze them in onboard analytical instruments; and to observe the environment around the rover.

MSL will investigate a site that shows clear evidence for ancient aqueous processes based on orbital data and undertake the search for past and present habitable environments. Assessment of present habitability requires an evaluation of the characteristics of the environment and the processes that influence it from microscopic to regional scales and a comparison of those characteristics with what is known about the capacity of life, as we know it, to exist in such environments. Determination of past habitability has the added requirement of inferring environments and processes in the past from observation in the present. Such assessments require the integration of a wide variety of chemical, physical, and geological observations.

MSL is not a life detection mission and is not designed to detect extant vital processes that would betray present-day microbial metabolism. Nor does it have the ability to image microorganisms or their fossil equivalents. MSL does have, however, the capability to detect complex organic molecules in rocks and soils. If present, these might be of biological origin, but could also reflect the influx of carbonaceous meteorites. More indirectly, MSL will have the analytical capability to probe other less unique biosignatures, specifically, the isotopic composition of inorganic and organic carbon in rocks and soils, particular elemental and mineralogical concentrations and abundances, and the attributes of unusual rock textures. The main challenge in establishment of a biosignature is finding patterns, either chemical or textural, that are not easily explained by physical processes. MSL will also be able to evaluate the concentration and isotopic composition of potentially biogenic atmospheric gases such as methane, which has recently been detected in the modern atmosphere. But compared to the current and past missions that have all been targeted to find evidence for past or present water, the task of searching for habitable environments is significantly more challenging (e.g., Grotzinger, 2009). Primarily, this is because the degree to which organic carbon would be preserved on the Martian surface – even if it were produced in abundance – is unknown.

The MSL mission has four primary science objectives to meet the overall habitability assessment goal. The first is to assess the biological potential of at least one target environment by determining the nature and inventory of organic carbon compounds, searching for the chemical building blocks of life, and identifying features that may record the actions of biologically relevant processes. The second objective is to characterize the geology of the landing region at all appropriate spatial scales by investigating the chemical, isotopic, and mineralogical composition of surface and near-surface materials, and interpreting the processes that have formed rocks and soils. The third objective is to investigate planetary processes of relevance to past habitability (including the role of water) by assessing the long timescale atmospheric evolution and determining the present state, distribution, and cycling of water and CO_2. The fourth objective is to characterize the broad spectrum of surface radiation, including galactic cosmic radiation, solar proton events, and secondary neutrons.

These observations and measurements will individually be of great scientific interest and importance, but the overall scientific goal of assessing present and past habitability of environments at the visited sites will only come from their comprehensive integration, and this is consequently a key feature of the proposed mission. Each of the ten instruments contributes to multiple science objectives, and most of the science objectives involve contributions from several instruments. Because of the cross-instrument nature of the science return, much of the tactical operations and science assessment will be coordinated through science theme groups comprising the entire MSL science team, as discussed in a later section. Strategic science operations, data analysis, and dissemination of results will be integrated by and coordinated through the MSL Project Science Group (PSG).

2.4 MSL Science Team

The MSL Science Team currently consists of the instrument investigation PIs, Co-Is, Collaborators, Project Scientist, Program Scientist, Deputy Project Scientists, and Investigation Scientists. Participating Scientists will be added to the team after selection. The MSL Science Team Rules of the Road document (Appendix B of this document) provides the principles, ground rules, and operations policies that will underpin the project's approach to managing the integrated scientific investigations, including data access, data sharing, data release, publication authorship privileges, and integrated instrument operations. All MSL Science Team members are expected to adhere to the Rules of the Road and any future updates approved by the PSG.

The MSL Project Science Group (PSG) is co-chaired by the MSL Project Scientist and the MSL Program Scientist and comprises the instrument PIs as members. 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. This is the list of MSL PSG Members:

- Project Scientist John Grotzinger, Caltech
- Program Scientist Michael A. Meyer, NASA Headquarters
- APXS PI Ralf Gellert, University of Guelph, Canada
- ChemCam PI Roger C. Wiens, Los Alamos National Laboratory
- CheMin PI David F. Blake, NASA Ames Research Center
- DAN PI Igor Mitrofanov, Space Research Institute, Russia
- MAHLI PI Kenneth S. Edgett, Malin Space Science Systems
- MARDI and Mastcam PI Michael C. Malin, Malin Space Science Systems
- RAD PI Donald Hassler, Southwest Research Institute
- REMS PI Javier Gómez-Elvira, Centro de Astrobiología/INTA, Spain
- SAM PI Paul Mahaffy, NASA Goddard Space Flight Center

2.5 Landing Site Selection

The MSL landing site will profoundly influence the nature and quality of the scientific return from the mission, as well as the pace and strategy for surface operations. An ideal landing site would: i) contain evidence suggestive of a past or present habitable environment; ii) meet or exceed all engineering and safety constraints; and iii) allow acceptable operational performance. A corollary to the first criterion is that the evidence for habitability, whether geological, chemical, or biological, would be preserved for, accessible to, and interpretable by the MSL payload. Operational performance can be impacted by terrain (e.g., more obstacles to navigate through) or temperatures (e.g., colder daytime temperatures result in energy being diverted to heaters).

The selection of the MSL landing site is informed through a series of community-led open workshops that have occurred in parallel with the design and development of the spacecraft. The workshops are organized by a NASA-appointed Landing Site Steering Committee, co-chaired by Dr. John Grant (Smithsonian Institution) and Dr. Matthew Golombek (JPL). Workshops in June 2006, October 2007, September 2008, and September 2010 considered over sixty sites, narrowing the list of candidate sites to four finalists at the time of this writing. The down-selections have been based on many factors including their scientific relevance and assessment against surface and atmospheric safety constraints. The final site and backup will be selected in the spring of 2011 after an additional community workshop and subsequent analyses by the MSL Project, science teams, and NASA officials. The selecting official is the NASA Associate Administrator for the Science Mission Directorate.

One of the programmatic goals of the MSL mission is to provide access to more of Mars' surface by removing or broadening the constraints present on previous missions and by not tailoring the design to any specific site or set of environmental conditions. Such a design also allows the final site selection to occur later in the process, providing more time to incorporate data and discoveries from the missions that precede MSL. Relative to previous landers, MSL can target a site with smaller uncertainty (25 km × 20 km landing error ellipse) and can land and operate over a wider range of latitudes (i.e., thermal environments) and elevations. In addition, the rover's driving capability is similar to its landing uncertainty, meaning that the rover can access targets near but outside of its error ellipse. This factor allows the exploration of regions that extend beyond the area safe for landing. All of the candidate landing sites contain features of interest both inside and beyond the bounds of the landing ellipse.

A list of the current candidate landing sites can be found in Table 1. These finalist sites have passed checks against engineering and safety criteria, though data acquisition and analyses are ongoing. From a scientific standpoint, sites with mineralogical (phyllosilicates or sulfates) and/or geological evidence (depositional fans, fluvial systems) for past aqueous activity, as detected from orbit, are thought to be the most relevant for the MSL science objectives and payload.

Table 1. Candidate MSL landing sites as of December 2010

Name	Location	Elevation (MOLA areoid)
Holden Crater	26.37°S, 325.10°E	-1940 m
Mawrth Vallis	24.01°N, 341.03°E	-2246 m
Eberswalde Crater	23.86°S, 326.73°E	-1450 m
Gale Crater	4.49°S, 137.42°E	-4451 m

Landing will occur in the afternoon, in late northern summer at $L_s \approx$ 151-158°. Landing site safety criteria, EDL capabilities, and ellipse parameters are described in the first web link below. The links also contain the presentations from the community workshops, and catalogs of the datasets from various orbital experiments that are relevant to site studies.
http://marsoweb.nas.nasa.gov/landingsites/
http://webgis.wr.usgs.gov/msl/

3 The Rover

3.1 Basic Description

The core of the MSL flight system used in the surface mission is the rover, which features an extensive scientific payload described later in this document. Figure 2 indicates the location of some of the major components on the rover. A similar figure showing the location of the instruments (Figure 9) is provided at the beginning of Section 4 of this document.

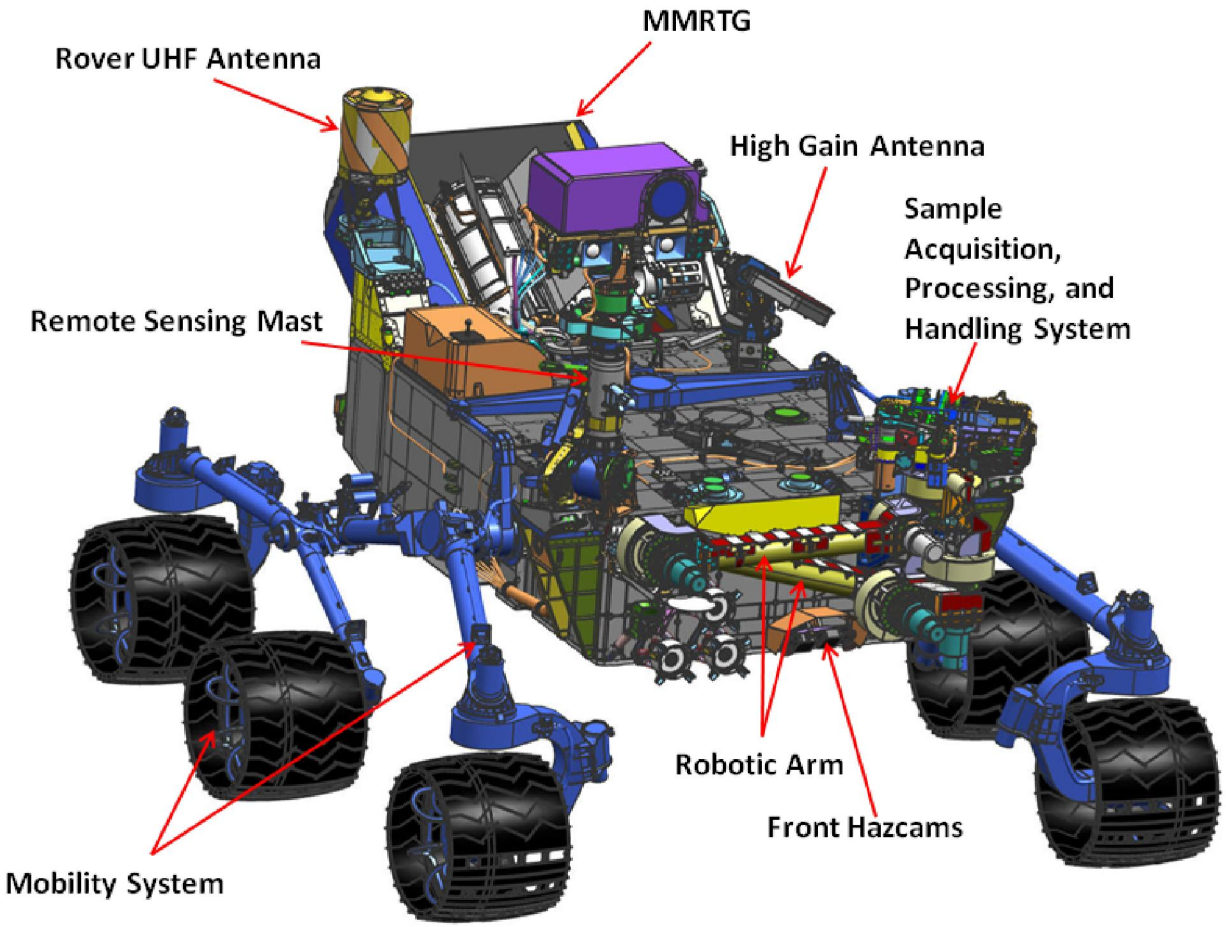

Figure 2. Drawing of the rover indicating some of the major components. Robotic arm is stowed (folded up) in front of the rover.

Overall characteristics of the rover include a total mass of ~900 kg, 2.8 m width, 3 m length (4.7 m long with robotic arm extended), 1.1 m top deck height, 2.2 m total height, and 84 kg instrument payload. The rover is a vehicle for remote operation on the Martian surface with the following capabilities:

- supports the science instrument payload investigations
- can traverse up to 100 to 200 meters per sol, depending on the terrain
- provides high-speed computational capability and substantial data storage
- provides X-band for Direct-to-Earth (DTE) and Direct-from-Earth (DFE) telecommunications, and the ability to communicate via UHF with Mars Reconnaissance Orbiter and Mars Odyssey (which will store and relay data to the Earth)

3.2 Mobility

The rover is a scaled version of the 6-wheel drive, 4-wheel steering system from the Mars Exploration Rover (MER). Based on the center of mass, the vehicle is required to withstand a static tilt of at least 50° in any direction without overturning. Fault protection will limit the rover from exceeding 30° tilts while driving. The design of the rocker-bogie allows the wheels to move over objects approximately as large as the wheel diameter (0.5 m). Clearance under the rover's body on flat ground is 66 cm. Each wheel has cleats and is independently actuated and geared, providing for climbing in soft sand and scrambling over rocks. Each front and rear wheel can be independently steered, allowing the vehicle to turn in place as well as execute arcing turns. The rover has a top speed on flat hard ground of ~4 cm/s but under autonomous control with hazard avoidance, the vehicle achieves an average speed of ~1.5 cm/s. Further discussion of the driving modes occurs later in the section on navigation.

3.3 Power

Rover power is provided by the Multi-Mission Radioisotope Thermoelectric Generator (MMRTG), which generates ~115 W of electrical power at the start of the landed mission and decays to ~110 W minimum at the end of mission. Peak power demand from the rover activities easily exceeds this however, and the rover has two Li-Ion rechargeable ~42 amp-hour batteries to allow for all activities. The batteries are expected to go through multiple charge/discharge cycles per Sol, with maximum allowed depth of discharge of ~53%.

3.4 Telecom

The surface telecommunications system uses three antennas, two for X-Band DTE/DFE (Direct to/from Earth), and a UHF antenna for relay to an orbiting asset. The X-band antennas are the Rover Low Gain Antenna (RLGA) and the High Gain Antenna (HGA). The HGA is used for either direct-to-Earth (DTE) or direct-from-Earth (DFE), while the RLGA is used primarily for DFE. The basic telecom requirement for surface operations on the HGA is to transmit at least at 160 bits per second to a 34-meter Deep Space Network (DSN) antenna, or 800 bits per second to a 70-meter DSN antenna. In safe mode, commands from the Earth will be received via the LGA, which does not require pointing. Limited capability for communications exists via the LGA (15 bits per second uplink at max range). Current expectations are for the typical daily uplink of commands via the HGA, taking approximately 15 minutes for a total volume of 225 kilobits. The HGA sits on a 2 degree-of-freedom gimbal, with 5 degree system pointing accuracy (including rover attitude knowledge), and is 0.28 meters in diameter.

The primary data return path for surface operations is via the UHF relay system, using the Mars orbiting assets, Mars Odyssey and Mars Reconnaissance Orbiter (MRO). The project intends for primary communications to go through MRO, with two passes a day primarily used to return data from the surface. Typically, it is expected that science decisions will be supported by returning 50 to 100 megabits of low-latency decision support data for the tactical process, and up to 800 megabits of data per sol total, depending on the landing site latitude selected. The mission is designed to return a minimum of 250 megabits per sol using two UHF passes. Communications with Odyssey are subject to necessity and available energy. The UHF subsystem has a pair of redundant Electra-Lite radios. If for any reason DTE/DFE via X-Band is not possible, the UHF passes can be used to command the rover instead. A single quad-helix antenna called the RUHF is mounted to the rover deck and used for either of the radios.

3.5 Engineering Cameras

In addition to science cameras described in Section 4 of this document, the MSL rover carries 12 engineering cameras (4 Navcams and 8 Hazcams), all of which share the same design (Table 2) as the MER engineering cameras described in Maki et al. (2003). The primary set of engineering cameras is a Navcam pair at the top of the mast, a front Hazcam pair mounted on the front panel of the rover body and a rear Hazcam pair mounted on the back panel of the rover body. Two pairs of the cameras provide redundant backups (an extra Navcam pair and an extra Front/Rear Hazcam pair). The redundant cameras are connected to the backup rover computer and are not expected to be used unless there is a problem with the primary rover computer and/or primary cameras. The engineering cameras are designed mainly to support operational activities such as rover navigation, localization, hazard detection, and robotic arm positioning. However, the operational distinction between science and engineering is only a convention; most downlinked Navcam/Hazcam image data will have value for both science and engineering. Each camera contains an electronic serial number readable in software, which uniquely identifies the camera and allows processing software to apply data processing on a camera-specific basis.

Table 2. Detector and electronics characteristics of the engineering cameras

Parameter	Value
Readout style	Frame transfer
Imaging area (pixels)	1024 × 1024
Pixel size (microns)	12 × 12
Dark current at 27 °C, imaging area (nA/cm^2)	<1.5
Gain (electrons/DN)	50
Full well capacity (electrons)	170,000
Linearity, for signals between 10 to 90% full well (no binning) (%)	> 99
Pixel-to-pixel nonuniformity at 20% full well and -20 °C (%)	< 1
Digitization (bits/pixel)	12
System readout noise (electrons)	25
CCD readout time (sec)	5.4
Exposure time range (sec)	0 to 335
Exposure time step size (msec)	5.1
On-chip binning size	4 × 1

The hazard-avoidance cameras (Hazcams) are mounted in stereo pairs; two pairs on the front panel of the rover body 68 cm above the ground when the rover is on hard flat terrain, and two pairs (one as a redundant backup) on the rear panel of the rover body 78 cm above the ground. Each Hazcam pair assembly includes two cameras mounted to achieve a stereo view (a 16 cm stereo baseline for each of the front pairs, and 10 cm for each of the rear pairs). Each Hazcam camera has a 124° × 124° Field of View (FOV) (180° diagonal), and a 600 - 800 nm band-pass filter. Depth of field is 0.1 m to infinity, the focal length is 5.58 mm, and best focus is at 0.5 m. The Hazcams provide imaging primarily of the near field (< 5 m) both in front of and behind the rover. These cameras will provide for onboard hazard detection using stereo data to build range maps. They also support science operations for selecting near field target and robotic arm operations.

The Navcams are mast-mounted stereo pairs with a spectral passband of 600-800 nm. Unlike MER, where much of the robotic arm workspace was blocked from view from the mast-mounted cameras, most of the robotic arm workspace for MSL will be viewable by the MSL Navcams, as well as the mast-mounted science cameras. The primary Navcam stereo pair is mounted near the top of the rover mast below the ChemCam mast unit, 1.99 meters above the ground when the rover is on hard flat terrain. The redundant Navcam pair is mounted 5 cm below the primary pair. Both Navcam pairs have a stereo baseline of 42.4 cm. The mast can point the camera pairs 360° in azimuth and ± 90° in elevation (up and down). The Navcams will be primarily used for navigation purposes and general site characterization, capable of providing 360° panoramic image mosaics and targeted images of interest, including terrain not viewable by the Hazcams. The Navcam stereo pair is boresighted with the Mastcam science cameras and Chemcam science instrument, and Navcam images will often be used for science target selection and analysis. The depth of field for each Navcam camera is 0.5 m to infinity, focal length is 14.67 mm, best focus is at 1m, and the FOV is 45° × 45° (67° diagonal).

The Hazcams will be calibrated radiometrically to an absolute accuracy of < 20% over their central 45° FOVs, and relative pixel-to-pixel accuracy of < 10% over their entire FOV. The Navcams will be radiometrically calibrated to an absolute accuracy of < 20% over their entire FOVs, and relative accuracy of < 5% over their entire FOV. Calibration of the MSL Hazcams and Navcams will follow the same plan as for the MER engineering cameras.

3.6 Navigation

Traverse forms a very significant part of MSL's mission, given its overall goal of exploring and assessing a local region on Mars' surface. Like MER, the MSL rover offers three primary modes of navigation. The first of these is the blind-drive, where rover planners have sufficient local imagery from the engineering cameras, to determine that a safe path exists, free of obstacles or hazards, and to command the rover to traverse some number of meters along that path. This length is usually limited by the visibility of distant terrain and ability to resolve hazards with the mast imagers. In this mode, the rover measures distance solely via the wheel odometry.

For a long traverse, the rover can select a path on its own by using hazard avoidance. Hazard avoidance requires the rover to stop frequently, on the order of a vehicle length, to acquire images with the Hazcams. The rover then analyzes the images for potential hazards, and selects a safe path. The algorithm on board has weights for path safety and how much the path corresponds to the desired direction of traverse. Visual odometry consists of another image-based check of the drive. The rover stops at a given interval, roughly every 10 meters, to capture images orthogonal to the drive direction with the Navcam. It then compares the most recent image to an image acquired before the last segment of traverse, looking for similar features to determine how far it has gone. This mode is also called “slip-check” mode. This mode typically provides more accurate measurement of distance, as it is possible for the rover to slip, or turn wheels without making full progress—in fact the rover could potentially identify if it was stuck before aggravating the situation with further attempts to traverse.

The final mode is drive with hazard avoidance and full-time visual odometry. The primary difference from the second mode described above is that the rover stops and performs the visual odometry analysis on the order of every half-vehicle length. This mode is useful when it is desired to perform a high precision approach of a target, and when the rover is traversing slippery or very steep terrain.

These modes differ significantly in the fraction of time spent rolling versus computing. From a speed perspective, blind drives are fastest, followed by hazard avoidance with slip check, and then hazard avoidance with visual odometry. For comparison, typical rates on a flat sandy surface are ~130 m/hr for blind drive, versus ~30 m/hr for hazard avoidance.

In addition to providing mobility navigation on the surface of Mars, the surface attitude control system is responsible for maintaining an onboard estimate of the rover orientation, which is used both by ground analysts for interpreting the science and engineering data returned as well as onboard for the pointing of the High Gain Antenna. The rover’s Inertial Measurement Unit is used to provide absolute tilt estimates relative to gravity as well as to propagate attitude during driving using gyros. Overall rover attitude knowledge (including heading) is determined from the position of the Sun using Navcams, similar to MER.

3.7 Remote Sensing Mast

The Remote Sensing Mast (RSM), shown in Figure 3, provides a tall geologist’s eye-level view from the cameras mounted at the top, ~2 meters above the Martian surface. The RSM head includes the ChemCam, Mastcams, and Navcams, with the ChemCam sitting inside of the remote warm electronics box (R-WEB). The R-WEB is a thermally controlled enclosure atop the mast. The RSM has the ability for azimuth and elevation control, and can slew at 5° per second. The RSM allows for full 360° (±181°) azimuth and ±91° elevation (zenith to nadir) range of motion. Mounted along the shaft of the mast are two booms for the REMS investigation.

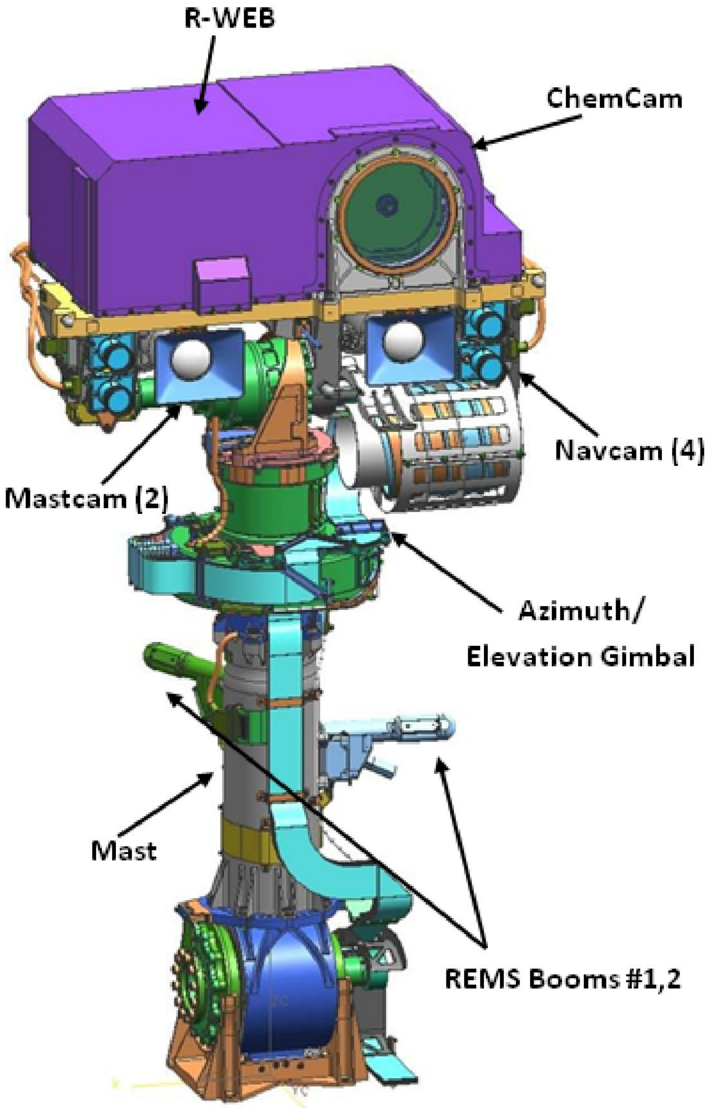

Figure 3. Remote Sensing Mast. The direction of the rover is into the page (the RSM is looking "backward").

3.8 Sample Acquisition, Processing, and Handling Subsystem

The Sample Acquisition, Processing, and Handling (SA/SPaH) subsystem is responsible for the acquisition of rock and soil samples from the Martian surface and the processing of these samples into fine particles that are then distributed to the analytical science instruments, SAM and CheMin. The SA/SPaH subsystem is also responsible for the placement of the two contact instruments, APXS and MAHLI, on rock and soil targets. SA/SPaH consists of a Robotic Arm (RA) and turret-mounted devices on the end of the arm, which include a drill, brush, soil scoop, sample processing device, and the mechanical and electrical interfaces to the two contact science instruments (Figure 4). SA/SPaH also includes drill bit boxes, the Organic Check Material (OCM), and an observation tray, which are all mounted on the front of the rover, and inlet cover mechanisms that are placed over the SAM and CheMin solid sample inlet tubes on the rover top deck. Figure 5 shows the location of these SA/SPaH components on the rover.

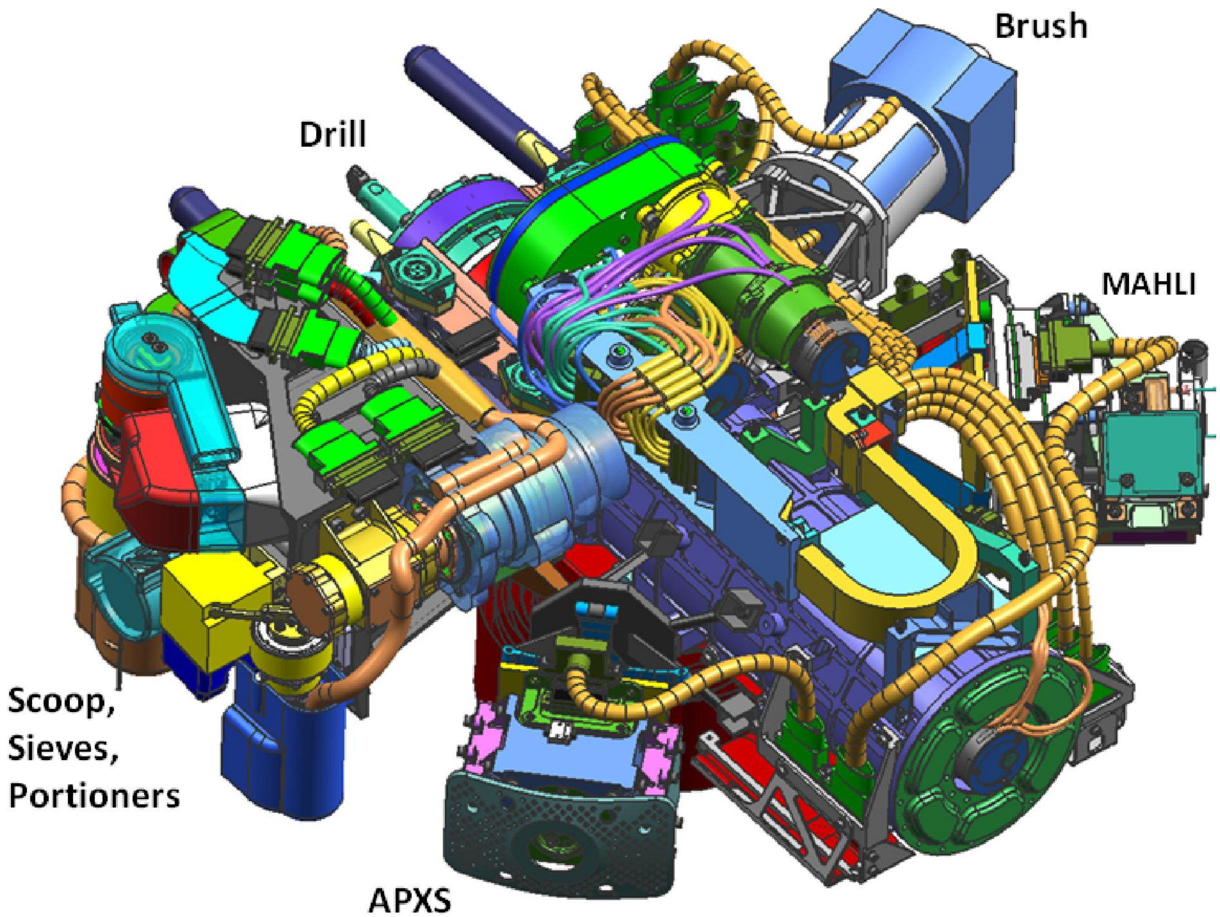

Figure 4. Diagram showing the turret-mounted devices on the end of the robotic arm: drill, brush, soil scoop, sample processing device (sieves, portioners), and the two contact science instruments, APXS and MAHLI. The devices are connected to the arm by the component shown in red on the underside of this drawing.

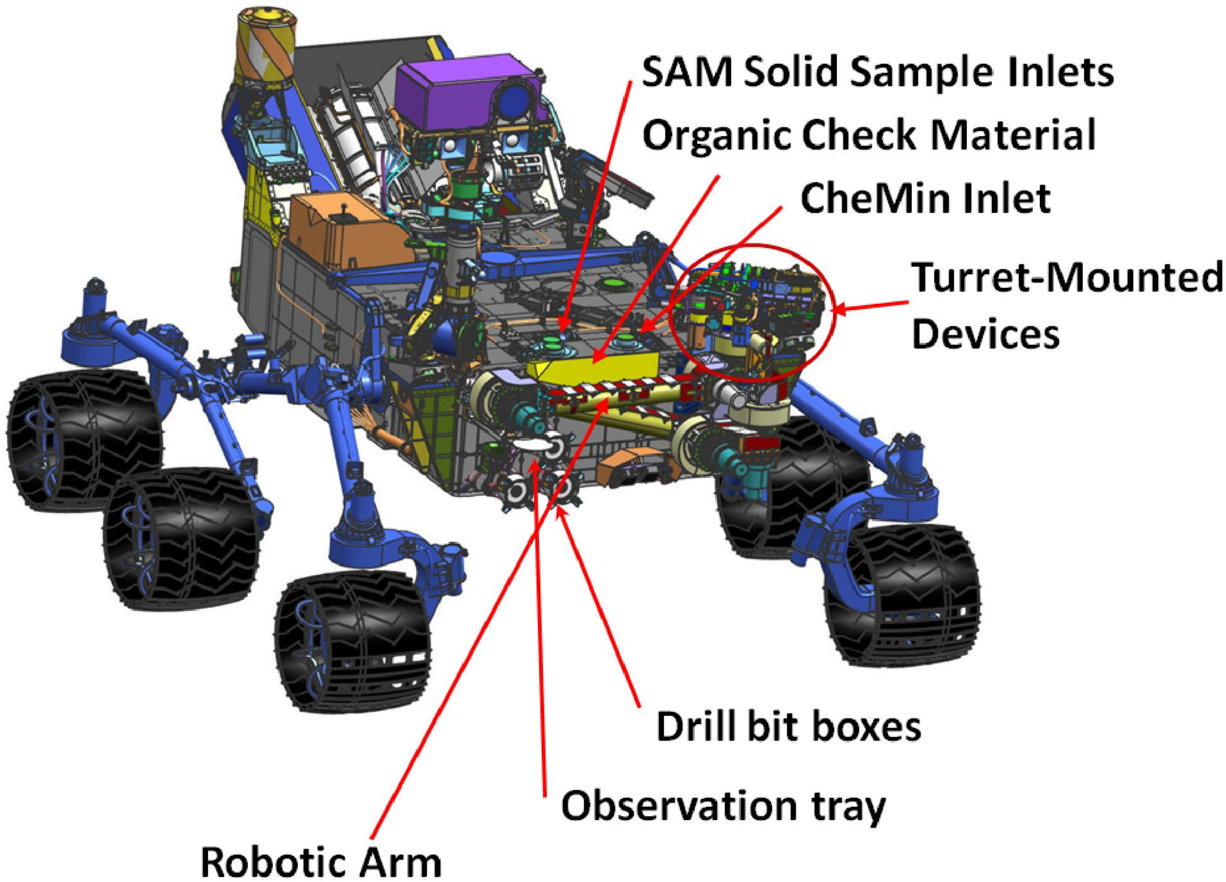

Figure 5. Diagram showing the location of SA/SPaH components on the rover. This is an older configuration with three spare drill bit boxes; the current design (see Figure 6) has two.

The Robot Arm (RA) is a 5 degree-of-freedom manipulator that is used to place and hold the turret-mounted devices and instruments on rock and soil targets, as well as manipulate the turret-mounted sample processing hardware. The 5 degrees of freedom are provided by a set of rotary actuators known as the shoulder azimuth joint, the shoulder elevation joint, the elbow joint, the wrist joint, and the turret joint. The joints are connected by structural elements with long links connecting the shoulder and elbow joints (known as the upper arm link) and connecting the elbow and wrist joints (known as the forearm link). When fully extended straight ahead in the rover forward drive direction, the center of the turret of the robotic arm is 1.9 m from the front of the rover body.

At the end of the RA is the turret structure on which 5 devices are mounted. The outer diameter of the turret plus the installed devices is 60 cm. Two of these devices are the science contact instruments APXS and MAHLI. The remaining three devices are associated with sample acquisition and sample preparation function: the Powder Acquisition Drill System (PADS), Dust Removal Tool (DRT), and the Collection and Handling for Interior Martian Rock Analysis (CHIMRA). The robotic arm can meet its positioning requirements for targets inside a volume called the robotic arm workspace. The workspace volume is an upright cylinder 80 cm diameter, 100 cm high, positioned 105 cm in front of the front body of the rover, and extending to 20 cm below the surface when the rover is on a smooth flat terrain.

In order to place and hold these turret-mounted devices on rock and soil targets, the current design of the RA is capable of exerting large forces between the turret-mounted hardware and the rock or soil surface. In particular, these large forces are required to stabilize the drill against a rock target in order to keep the device from “walking” across the surface of a rock when first engaging the rock surface with the cutting bit. The RA achieves this function by first placing the drill against the rock surface and then “overdriving” the actuators so that the entire system winds up against the overall stiffness of the RA. The sizing of the RA actuators allows this mechanism to produce more than 240 N at the tip of the arm in certain arm configurations. During motion, the tip speed of the RA is expected to be on the order of 1 cm/sec.

The PADS is the device that is responsible for acquiring powdered rock samples from up to 5 cm inside the surface of a rock. When the RA places and holds the drill bit against a rock surface with 240 to 300 N axial load, the PADS can then acquire the rock sample without requiring any motion of the RA. The PADS has the following capabilities: (a) translate the drill bit down and into the rock surface, (b) rotate the drill bit (0 to 150 rpm) in order to cut the rock material, (c) provide voice-coil percussion (1800 bpm, 0.4 to 0.8 J impact energy) to the drill bit for drilling and powdering of rock sample, and (d) exchange the drill bit from the drill. The drill both penetrates the rock and powders the sample to the appropriate size for analytical instrument use. The powder travels up an auger in the drill and into a chamber with a transfer tube connection to the CHIMRA processing unit. Movement of the powder through CHIMRA is driven by gravity (by changing the position and orientation of the robotic arm) and vibration.

The diameter of the hole in a rock after drilling is 1.6 cm in diameter and up to 5 cm deep, depending on the surface topography of the rock. Material from the upper ~1.5 to 2 cm of the drill hole is deposited on top of the rock surrounding the drill hole and does not make it into CHIMRA and the Analytical Laboratory instruments. Below this depth, the sample acquired is transferred to CHIMRA for sieving and portioning.

The grain size distribution of the drilled powder and the temperatures to which the powder is heated during drilling will depend on the nature of the rock being drilled, the final drill design and performance, and operating parameters selected for use on Mars (rotation and percussion parameters, on-off cycles, etc). Tests so far on prototype drills over a range of operational parameters and rock types have yielded samples with ~90% of the bulk material generated by the drill capable of passing through a 150 μm sieve and 100% passing through a 1 mm sieve. Heating of the sample appears to be minimal, but tests have yet to be done to understand the likely degree of heating on Mars.

In the course of gathering a sample, it is possible the rover arm might slip, resulting in non-nominal torques on the bit while in contact with a rock. This might cause the bit to become stuck in the rock, and if this happens, the drill can disengage from the bit and SA/SPaH can reload another bit. Also during the life of the mission, if the drill is used on particularly hard material such as coarse-grained quartz-rich rocks, the bit might wear down and become unusable. As such, the drill is capable of exchanging bits with two extra spare bits located in containers called “bit boxes” on the front of the rover (Figure 6). Once the drill has discarded a worn bit, the robotic arm will be used to position the drill relative to a new bit and autonomously engage and capture the spare bit onto the drill stem. Testing so far has shown that prototype versions of the drill can penetrate rocks as hard as massive fine-grained basalt without substantial wear on the drill bit.

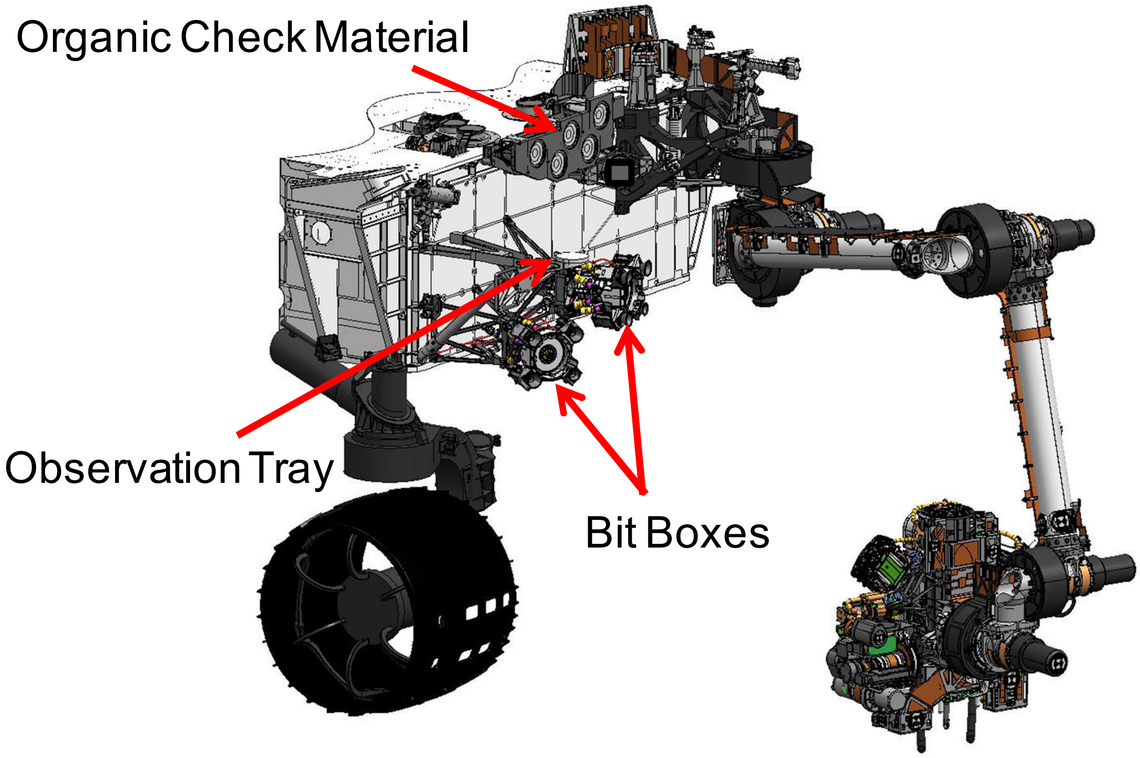

Figure 6. Diagram of a portion of the front of the rover, showing location of the two bit boxes, observation tray above the bit boxes, and the five organic check material canisters.

Soil samples are acquired with CHIMRA's clam-shell scoop mechanism (Figure 7), which can collect loose soil material from depths of up to 3.5 cm. The scoop can also collect unconsolidated samples from rover wheel-dug trenches, depending on the geometry of the trench, which might access material as deep as ~20 cm below the original surface. (Also, depending on the geometry of the trench, APXS and/or MAHLI can be used to examine the material in a trench). The volume of a scooped soil sample is expected to be between 1000 and 30,000 mm^3.

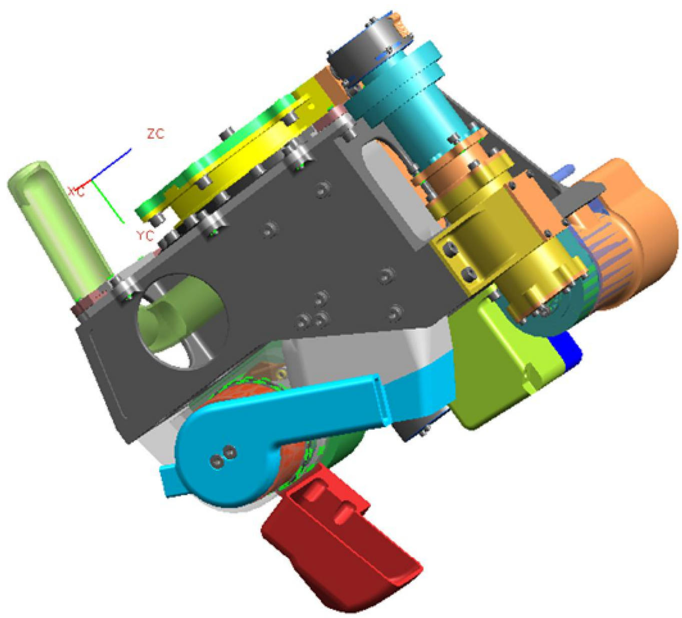

Figure 7. Diagram of CHIMRA, showing the scoop in an open position (indicated here in red).

The CHIMRA is a device that sieves and portions the samples from the scoop and the drill which are then distributed to the analytical instruments, SAM and CheMin. Various chambers and labyrinths within the mechanism are used to sort and sieve the drilled rock or scooped soil material. This sorting function is carried out by rotating the robotic arm turret actuator with respect to the gravity vector. In addition to the scoop actuator, the CHIMRA also carries a vibration actuator that helps to facilitate material movement within the CHIMRA and also during the delivery action when the CHIMRA drops material into the instrument inlets.

The CHIMRA provides mechanisms for sieving particles to less than 150 µm, mixing the samples that pass through the 150 µm sieve, and portioning the samples into the appropriate volume (45 to 65 mm^3 per portion) for distribution to the SAM and CheMin instruments. When using the 150 µm sieve, it is expected that the CHIMRA will typically generate sufficient quantity of sieved material for at least 6 total portions, if more than one is desired (3 portions are intended to be available per instrument). The CHIMRA also provides the capability for sieving particles to less than 1 mm and portioning that material into an appropriate volume for distribution to the SAM instrument (45-130 mm^3 per portion). CheMin cannot be given this type of coarser-grained sample because the particles are too large for its sample cells. When using the scoop and 1 mm sieve, only one portion can be generated per scoop. The sieves are mounted to mechanisms that impart shock into the sieves to clear and clean the sieve screens to help prevent cross contamination and minimize sieve clogging throughout the mission life.

3.9 Instrument Inlet Covers

The SA/SPaH subsystem also provides covers that protect the SAM and CheMin solid sample inlets from being contaminated by particulates from the atmosphere or rover deck. These covers are mounted on top of each solid sample inlet (locations shown in Figure 5) and are opened and closed using a motor for each one. During sample delivery, the instrument inlet cover is opened and the CHIMRA sample chamber is then positioned over top of the exposed solid sample inlet. Once the CHIMRA has dropped the sample into the solid sample inlet, the inlet cover is closed.

3.10 Dust Removal Tool

The Dust Removal Tool (DRT) is mounted to the turret of the robotic arm and can be used to remove the dust and loose material off of rock surfaces by clearing it away with stainless steel wire brushes. The design of the DRT (Figure 8) is different from the Rock Abrasion Tool brushes on the Spirit and Opportunity rovers, but is expected to have a similarly effective dust removal capability. A single actuator mechanism rotates the brushes and relies on the robotic arm to position it at a desired standoff distance from a target surface. The area to be cleared with the DRT has a minimum circular area of 45 mm diameter. The DRT is also expected to be used to clear off loose material from the observation tray.

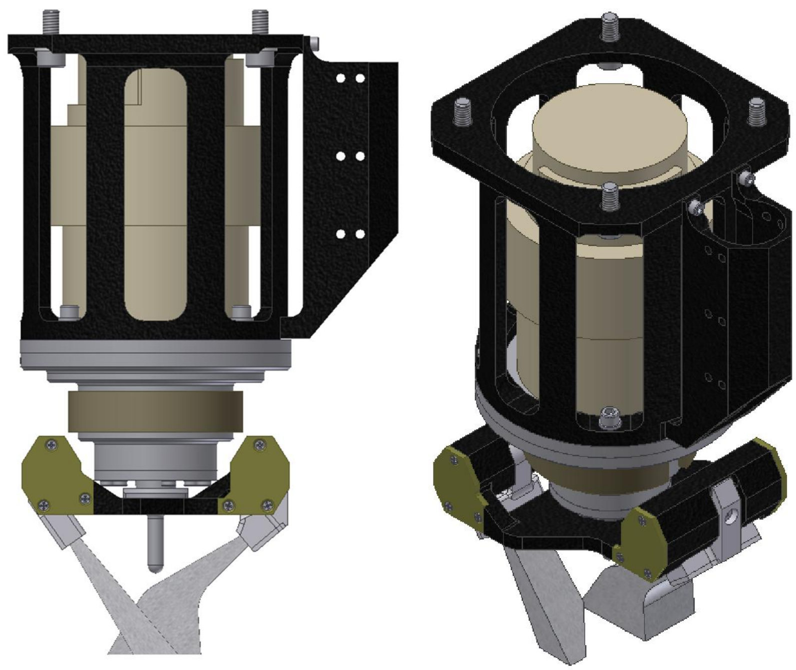

Figure 8. Diagram showing the design of the DRT, from two different view orientations.

3.11 Observation Tray

An observation tray is provided to allow processed samples delivered by CHIMRA to be observed by APXS and MAHLI. The design is not final at the time of writing this document, but current plans are that it will be a simple, flat titanium metal tray ~7.3 cm diameter, mounted on the front of the rover (Figure 6). Soil and rock samples that have passed through the 150 µm sieve of CHIMRA can be deposited on the tray, observed by the APXS and MAHLI, and subsequently removed from the tray by the DRT brushes. After delivering sieved material (soil or rock) to SAM and/or CheMin, the remainder of the sieved material can be analyzed in this way. There may be other options for use of the tray (such as delivery of scooped soil passing the 1 mm sieve to the tray), but none can be guaranteed at this time.

3.12 Organic Check Material

Steps have been taken to ensure that the SAM measurements of soil and rocks on Mars do not contain terrestrial contaminants above the SAM detection levels (ten Kate et al., 2008). However, it is likely that a slight amount of terrestrial contamination may be present despite our best efforts. To assess the characteristics of organic contamination at five different times in the mission, five bricks of Organic Check Material (OCM) mounted in canisters on the front of the rover (Figure 6) will be available for end-to-end sample handling tests on Mars. Each OCM brick can be drilled, sieved and portioned in CHIMRA, and delivered to SAM (and optionally also to CheMin), with the OCM drilled powder following the same pathway as for drilled Martian rocks. Each brick is made of porous amorphous silicon dioxide ceramic with 30% interconnected porosity. The bricks are doped with a low concentration of 3-fluorophenanthrene and 1-fluoronapthalene, which are synthetic organic compounds not found in nature on Earth and not expected on Mars. Each of the bricks is sealed in its own canister and under vacuum until it is drilled into on Mars. Each OCM canister is intended to be sampled only once, since breaking the seal permits an unknown level of reactivity between the brick and the Martian environment, resulting eventually in a sample no longer known to be a calibrated control. Contamination buildup on the outer surface of the sealed canister is not a concern, since the upper ~1 cm of brick drilled into will not go into CHIMRA. SAM measurements on Mars of the delivered OCM samples will be used to check whether SA/SPaH transfers terrestrial organic contamination to the samples; whether organic volatiles are lost by the process of acquisition, portioning, and distribution of samples; and whether complete sample portions have been delivered to SAM sample cups. Although the OCM material is X-ray amorphous, it could be used to check the level of end-to-end cross contamination on Mars from sample to sample in CheMin, by looking for residual XRD pattern features or residual XRF element peaks (residual from previously acquired samples) in an OCM-filled sample cell.

4 Science Instrument Investigations

Figure 9 shows the location of the 10 science instruments on the rover. There are three main types of instruments, the contact science instruments APXS (Alpha-Particle X-ray Spectrometer) and MAHLI (Mars Hand Lens Imager) on the end of the robotic arm; the remote sensing instruments ChemCam (Laser-Induced Remote Sensing for Chemistry and Micro-Imaging) and Mastcam (Mast Cameras); the environmental instruments DAN (Dynamic Albedo of Neutrons), MARDI (Mars Descent Imager), RAD (Radiation Assessment Detector), and REMS (Rover Environmental Monitoring Station); and the analytical laboratory instruments CheMin (Chemistry and Mineralogy) and SAM (Sample Analysis at Mars).

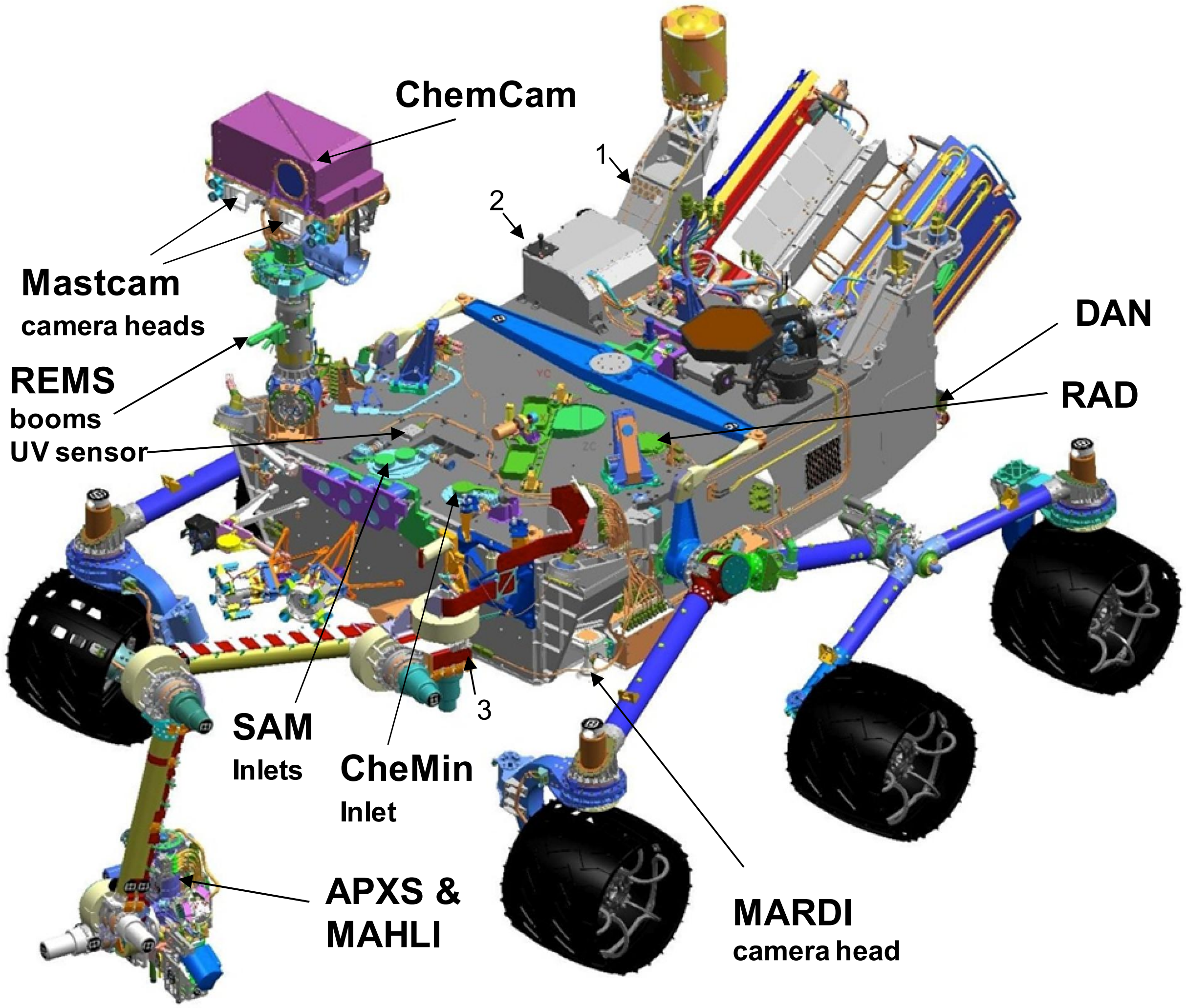

Figure 9. Location of the instruments on the MSL rover. CheMin and SAM are inside the rover chassis. APXS and MAHLI are mounted on the turret on the end of the robotic arm. Their locations on the turret are shown in Figure 4. An arrow is pointing to the DAN detector and electronics. The DAN pulsing neutron generator is on the opposite mirror side of the rear of the rover. The location of calibration targets is shown for ChemCam (1) and Mastcam (2). The calibration targets for APXS and MAHLI (3) are located on a side of the robotic arm's azimuth actuator housing, hidden from view in this diagram.

4.1 APXS (Alpha-Particle X-ray Spectrometer)

The APXS (Alpha-Particle X-ray Spectrometer) for MSL is an improved version of the APXS that flew successfully on Pathfinder and the Mars Exploration Rovers Spirit and Opportunity (Rieder et al., 1997, 2003; Gellert et al., 2006). The MSL APXS takes advantage of a combination of the terrestrial standard methods Particle-Induced X-ray Emission (PIXE) and X-ray fluorescence (XRF) to determine elemental chemistry. It uses curium-244 sources for X-ray spectroscopy to determine the abundance of major elements down to trace elements from sodium to bromine and beyond.

The instrument (Figure 10) consists of a main electronics unit in the rover's body and a sensor head mounted on the robotic arm. Measurements are taken by deploying the sensor head towards a desired sample, placing the sensor head in contact or hovering typically less than 2 cm away, and measuring the emitted X-ray spectrum for 15 minutes to 3 hours without the need of further interaction by the rover. At the end of the measurement, the rover retrieves the science data of 32 kilobytes, containing up to 13 consecutively taken spectra and engineering data. The internal APXS software splits the total measurement into equal time slots with an adjustable cycle time parameter. This allows us to check for repeatability and to select spectra with sufficient spectral quality.

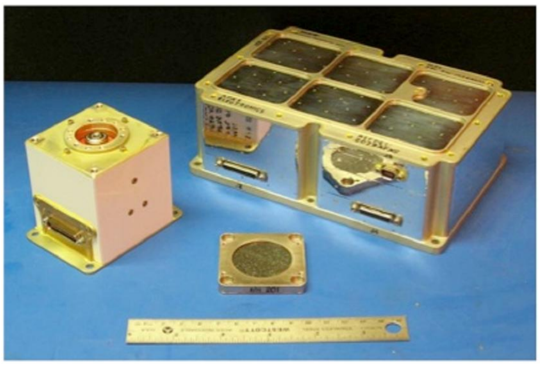

Figure 10. APXS hardware: sensor head (left), electronics unit (right), and calibration target (middle front).

The MSL APXS can activate an internal Peltier cooler for the X-ray detector chip. This results in a sufficient spectral FWHM of below 200 eV at 6.4 keV below ~ -5 °C and best FWHM of < 150 eV below ~ -15 °C environmental temperature. Compared to the APXS on MER, where the best FWHM was reached at temperatures below ~ -45 °C, this allows a significantly larger operational time window for APXS analysis.

The MSL APXS has approximately 3 times the sensitivity for low Z (atomic number) elements and approximately 6 times for higher Z elements than the MER APXS. A full analysis with detection limits of 100 ppm for Ni and ~ 20 ppm for Br now requires 3 hours, while quick look analysis for major and minor elements at ~ 0.5% abundance, such as Na, Mg, Al, Si, Ca, Fe, or S, can be done in 10 minutes or less.

On MER, the elements detected by the APXS in rock and soil samples are typically Na, Mg, Al, Si, P, S, Cl, K, Ca, Ti, Cr, Mn, Fe, Ni, Zn, and Br (e.g., Rieder et al., 2004; Gellert et al., 2006). Elevated levels of Ge, Ga, Pb, and Rb were found in some of the MER samples (e.g., Clark et al., 2007). A comparison of spectra from the MER and MSL APXS is shown in Figure 11.

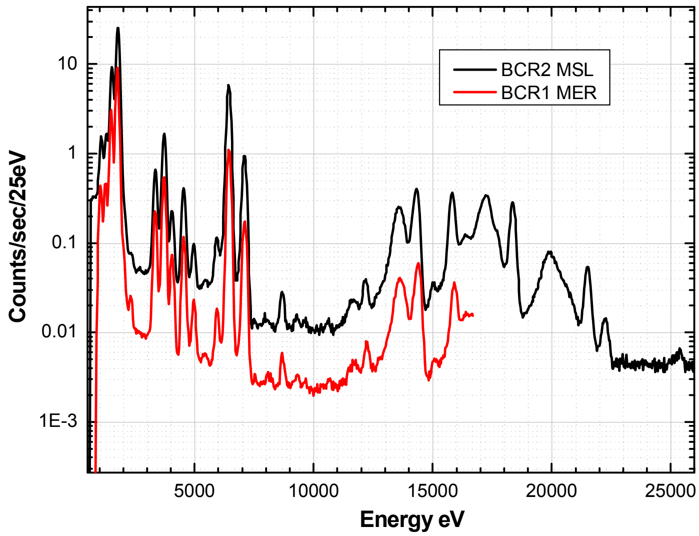

Figure 11. A direct comparison of spectra taken of the reference material BCR with the MER and MSL APXS instruments. The MSL energy range has been extended to about 25 keV, where additional Compton and Rayleigh backscattered X-ray peaks can be identified. The overall sensitivity (signal per time) is increased by about a factor of three for low Z elements and ~ 6 for high z elements above Ti due to added 30 mCi sealed Cm^{244} sources. The peak to background ratio is comparable. No significant additional background from the MSL MMRTG is expected.

The sampled area is about 1.7 cm in diameter when the instrument is in contact with the sample (as shown in Figure 12). A standoff results in gradually lower intensity and an increased diameter of the measured spot. Low Z element X-rays stem from the topmost 5 μm of the sample, higher Z elements like Fe are detected from the upper ~50 μm. Sample preparation is not needed; the APXS results average the composition over the sampled area and the oxide abundances measured are renormalized to 100%. However, on MSL, a dust removal tool (brush) is available to remove loose material from a rock surface before making an APXS measurement.

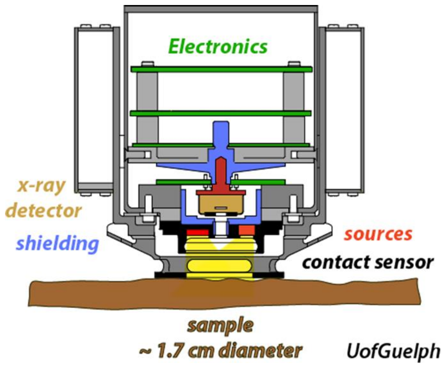

Figure 12. Schematic diagram of the APXS sensor head, showing the relationship between the radioactive sources, sample surface, and silicon drift X-ray detector.

The major improvements and changes compared to the MER APXS are:

- Improved sensitivity by a factor 3 giving full analysis within ~3 hours
- Additional improved sensitivity for high Z elements by increased X-ray source strength
- Operable during Martian day by using Peltier cooler for the X-ray detector
- Basaltic calibration target mounted on the rover (on the robotic arm azimuth actuator housing), dedicated for the APXS
- No alpha channel (no Rutherford Backscattering spectroscopy)
- Compressed short duration X-ray spectra (~10 seconds) can be used to steer the arm movement in a "proximity mode"

The main objective of the APXS is to characterize the geological context of the rover surroundings and to investigate the processes that formed the rocks and soils. The high precision and low detection limits, especially for salt forming elements like S, Cl, and Br, allow identification of local anomalies and guided in-situ sample selection for the analytical instruments of MSL. The rover observation tray for processed samples will allow the APXS to provide additional characterization of the samples collected and prepared for the analytical instruments, connecting the analytical instrument results with the in-situ samples. MSL sample preparation with the brush will allow in-situ APXS investigations of thin alteration rinds or near-surface layers or veins which cannot be collected by the drill for the analytical instruments. Another important aspect of the APXS investigation will be to relate the chemical composition of the MSL landing site and the results from the MSL payload to what has been found by the previous landed missions, which used similar X-ray spectroscopy methods.

The APXS will be fully calibrated using standard geological samples in the laboratory. An onboard basaltic rock slab, surrounded by a nickel plate, will be used periodically to check the performance and calibration of the instrument. The data analysis is theoretically well understood and delivers unambiguous element identification and accuracy on the order of ~10%, mainly limited by microscopic sample heterogeneity (i.e., grain size effects). The APXS data analysis is fast and allows a quick turnaround of results used for tactical rover operations.

The elemental data can be used to extract normative mineralogy either from scratch or using constraints from the mineralogy provided by CheMin. A newly developed method (Campbell et al., 2008) using the backscattered peaks of the primary X-ray radiation allows detection of X-ray invisible compounds like bound water or carbonates, if present in significant amounts (greater than ~5% by weight).

A list of science team members and their roles and areas of expertise is provided in Table 3.

Table 3. APXS science team members

Name	Affiliation	Role, Expertise
Ralf Gellert, PI	University of Guelph, Canada	Calibration and data analysis, instrumentation, *
Albert Yen, Co-I	Jet Propulsion Laboratory	*
Steve Squyres, Co-I	Cornell University	*
Iain Campbell, Co-I	University of Guelph	Calibration and data analysis
Penny King, Co-I	University of New Mexico	Hydrated salts calibration, *
Laurie Leshin, Co-I	NASA Headquarters	*
John Spray, Co-I	University of New Brunswick, Canada	Heterogeneities using MAHLI and APXS, *
Guenter Lugmair, Co-I	Scripps Institute	*
*Mineralogy and geology of Mars, water interaction, and comparison of APXS results from MER and Pathfinder.		

4.2 ChemCam (Laser-Induced Remote Sensing for Chemistry and Micro-Imaging)

4.2.1 Introduction

The ChemCam instrument package consists of two remote sensing instruments: the first planetary science Laser-Induced Breakdown Spectrometer (LIBS) and a Remote Micro-Imager (RMI). The LIBS provides elemental compositions, while the RMI places the LIBS analyses in their geomorphologic context. Both instruments will help determine which rock and soil targets within the vicinity of the rover are of sufficient interest to use the contact and analytical laboratory instruments for further characterization. ChemCam also can analyze a much larger number of samples than can be studied with the contact and analytical laboratory instruments. For example, the ChemCam team anticipates making daily analyses of the soil at the rover location to understand variations within the soils both locally and regionally. Furthermore, it can provide valuable analyses of samples that are inaccessible to other instruments, such as vertical outcrops where LIBS can target individual strata using its submillimeter beam diameter. ChemCam has the capability, but is not required, to provide passive spectroscopy data of rocks and soils on Mars. The spectral range covered by LIBS is not typical of passive spectroscopy instruments, making it more difficult to know what information can be useful from the spectra. However, the passive spectroscopy does not have the distance limitation that LIBS does.

Additional information about ChemCam can be found in the publications listed in the "Publications" link on the web site http://libs.lanl.gov.

4.2.2 LIBS Instrument

The LIBS instrument uses powerful laser pulses, focused on a small spot on target rock and soil samples within 7 m of the rover, to ablate atoms and ions in electronically excited states from which they decay, producing light-emitting plasma. The power density needed for LIBS is > 10 MW/mm^2, which is produced on a spot in the range of 0.3 to 0.6 mm diameter using focused, ~14 mJ laser pulses of 5 nanoseconds duration. The plasma light is collected by a 110 mm diameter telescope and focused onto the end of a fiber optic cable. The fiber carries the light to three dispersive spectrometers which record the spectra over a range of 240 - 850 nm at resolutions from 0.09 to 0.30 nm in 6144 channels (example shown in Figure 13). The spectra consist of emission lines of elements present in the samples. Typical rock and soil analyses yield detectable quantities of Na, Mg, Al, Si, Ca, K, Ti, Mn, Fe, H, C, O, Li, Sr, and Ba. Other elements often seen in soils and rocks on Earth include S, N, P, Be, Ni, Zr, Zn, Cu, Rb, and Cs. It is anticipated that 50-75 laser pulses will be required achieve the desired 10% accuracy for major elements at 7 m distance.

The advantages of the LIBS instrument are:

- Remote elemental analysis with no sample preparation
- Ability to remove dust and weathering layers with repeated laser pulses trained on the same spot
- Simultaneous analysis of many elements
- Low detection limits for a number of minor and trace elements, including Li, Sr, and Ba
- Rapid analysis; one laser shot can constitute an analysis, though many spectra are often averaged for better statistics, still only taking a few seconds
- Small analysis spot size of ≤ 0.6 mm diameter
- Ability to identify water and/or hydrated minerals
- Low power consumption resulting from very short analysis times

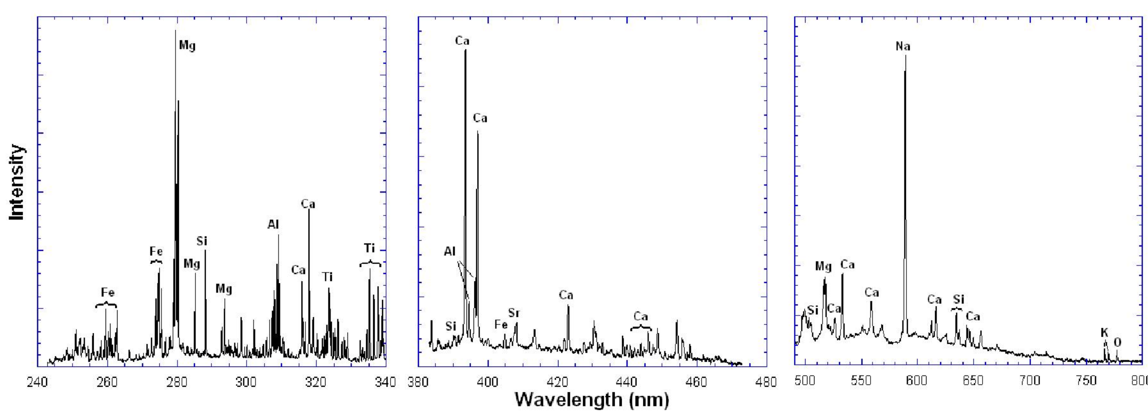

Figure 13. LIBS spectrum of basalt standard GBW07105 taken with the ChemCam engineering model at 5 m distance in 7 Torr (9.3 mbar) of atmosphere. The major emission lines are labelled.

4.2.3 RMI Instrument

The Remote Micro-Imager (RMI) is intended as a context imager for the LIBS, though unlike LIBS, it has no restrictions on the distance to the targets it images. It images through the same telescope as the LIBS, with the camera wavelength response shown in Figure 14.

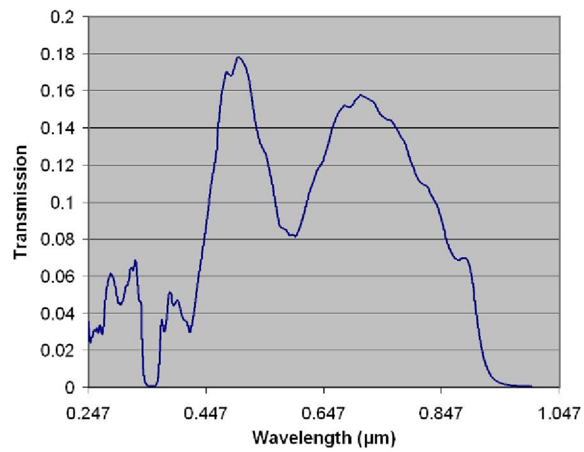

Figure 14. Wavelength response of the RMI.

The detector is a 1024 × 1024 pixel CCD. The RMI has a field of view of 19 milliradians. Due to optimization of the telescope for LIBS, the RMI resolution is not pixel-limited, and is approximately 100 microradians. The RMI can clearly distinguish the submillimeter LIBS spot on a metal plate at any distance within range of the LIBS. LIBS spots on rocks are more difficult to distinguish, but will be known from the pixel mapping, so the context of the LIBS spot can be determined.

4.2.4 Types of Investigations

The ChemCam instrument suite will be used to pursue the following investigations:

1. Rapid remote rock identification, which will be the main method of rapidly determining whether a given sample is similar to or different from rocks already encountered during the mission, and if the latter, whether the sample warrants investigation by the analytical laboratory instruments.
2. Quantitative elemental analyses, including trace elements, to support the MSL science objectives. Whole-rock analyses will require a number of (< 1 mm diameter) analysis spots on the same rock. Quantitative analyses will rely on using both the onboard calibration standards as well as comparison with LIBS analyses of standards in terrestrial laboratories.
3. Soil and pebble composition surveys. The ChemCam team plans to make a measurement of the soil near the rover each sol to document the range of soil compositions over which the rover traverses. These measurements may signal the presence of a new geological region, and will tell about the compositional similarity of the dust from place to place on Mars. The RMI can provide documentation on soil grain sizes without the need for placement of the contact instruments.
4. Detection of hydrated minerals. LIBS sensitivity for hydrogen is unique and will be an important indicator of bound water in minerals.
5. Depth profiles of rock weathering layers. LIBS can provide weathering profiles on a fine scale for small features, a unique capability.
6. Rapid remote identification of surface ices/frosts. LIBS can unambiguously detect water ice.
7. Geomorphology and imaging science. The high resolution imaging provided by RMI will enable detailed studies of the weathering processes of surfaces, and provide opportunities to image closeup many details with comparable or slightly higher resolution than Mastcam and without the need to drive up to a sample and deploy contact instruments.

8. Complement other techniques for rock identification in cases of dust or weathering. ChemCam can use its laser to remove dust or weathering surfaces to aid other instruments in their investigations.
9. Assist with Sample Acquisition, Processing, and Handling (SA/SPaH). ChemCam analyses can guide decisions on which samples within the robotic arm workspace should be sampled for in situ instrument analyses. ChemCam can provide imaging and compositional analyses on the samples being obtained for the in situ instruments. The small analysis spot size will be important in this regard. For example, without ChemCam the connection between a given XRD pattern taken by the analytical instruments and a distinctive mineral grain seen in the images might only be inferred at best.

4.2.5 Analysis Sequences

A measurement with ChemCam can take many forms due to its versatility. However, for illustrative purposes, Figure 15 shows a potential analysis sequence that acquires RMI images before and after the LIBS analysis. This type of sequence would be most often used for rapid rock identification. Each analysis of this type should take six minutes or less, excluding thermal delays. A thermoelectric cooler (TEC) is turned on to cool the detectors some minutes prior to instrument turn-on. The target is acquired by motion of the rover mast elevation and azimuth gimbals. The instrument is turned on, and the LIBS laser and the autofocus laser (continuous-wave, or CW laser) are warmed if needed. The telescope is focused on the target. RMI image acquisition and LIBS analyses are performed, and a

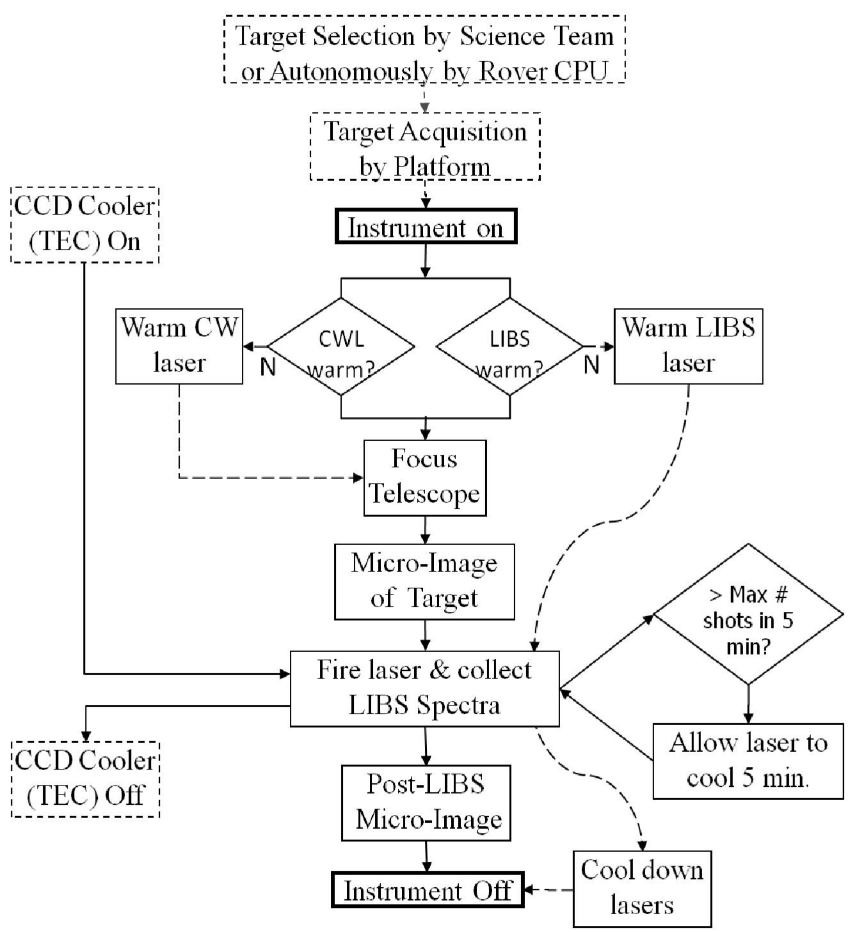

Figure 15. Typical ChemCam analysis sequence.

background (laser-off) spectrum is taken. The mast can then acquire other targets and the focus and shoot sequence can be repeated. Other types of analyses will include:

- Depth profiles > 0.5 mm, requiring > 500 laser shots on the same spot.
- Soil surveys, probably utilizing much the same analysis sequence as shown in Figure 15.
- Quantitative analyses, which will require a number of analysis spots on a single rock, each of these probably similar to Figure 15. Quantitative analyses would be carried out in conjunction with:
- Calibration targets. These are mounted on the rover and are used to calibrate the LIBS spectra.
- Miscellaneous images independent of any LIBS analyses. These will be used to characterize samples for the analytical laboratory, for general geomorphology studies, and to provide the highest resolution images of distant features.
- Passive UV-visible spectra. The LIBS spectrometers provide the opportunity for passive spectra taken using ambient sunlight and without the laser plasma.

4.2.6 Instrument Description

Figure 16 is a functional block diagram of the ChemCam suite. Photos are shown in Figure 17. The package consists of two separate units – “Body Unit” and “Mast Unit,” which are further broken down into modular components. The spectrometers and data processor are in the Body Unit, while the laser, imager, telescope, and focus laser are in the Mast Unit. The ChemCam Mast Unit is mounted on the rover mast just above Mastcam and Navcam. The boresight, at a height of 2.1 m above the ground, is coaligned with both Mastcam and Navcam. The Mast Unit is provided by CESR (funding from CNES), while LANL is responsible for the Body Unit. JPL is responsible for the fiber optic cable that transmits light from the telescope to the spectrometers. JPL also provided the thermoelectric cooler that cools the spectrometer CCDs. Parts and targets for the onboard calibration target were provided by C. Fabré (Nancy), V. Sautter (MNHN, Paris), D. Vaniman (LANL), and D. Dyar (Mount Holyoke College). The onboard rover calibration targets for LIBS consist of natural and synthetic volcanic glasses (Fabré et al., 2009, 2010) and ceramics consisting of mixtures of smectite and kaolinite with anhydrite and basalt to simulate Martian sedimentary samples (Vaniman et al., 2009). Also included is a graphite disk for carbon identification and a titanium plate for general use.

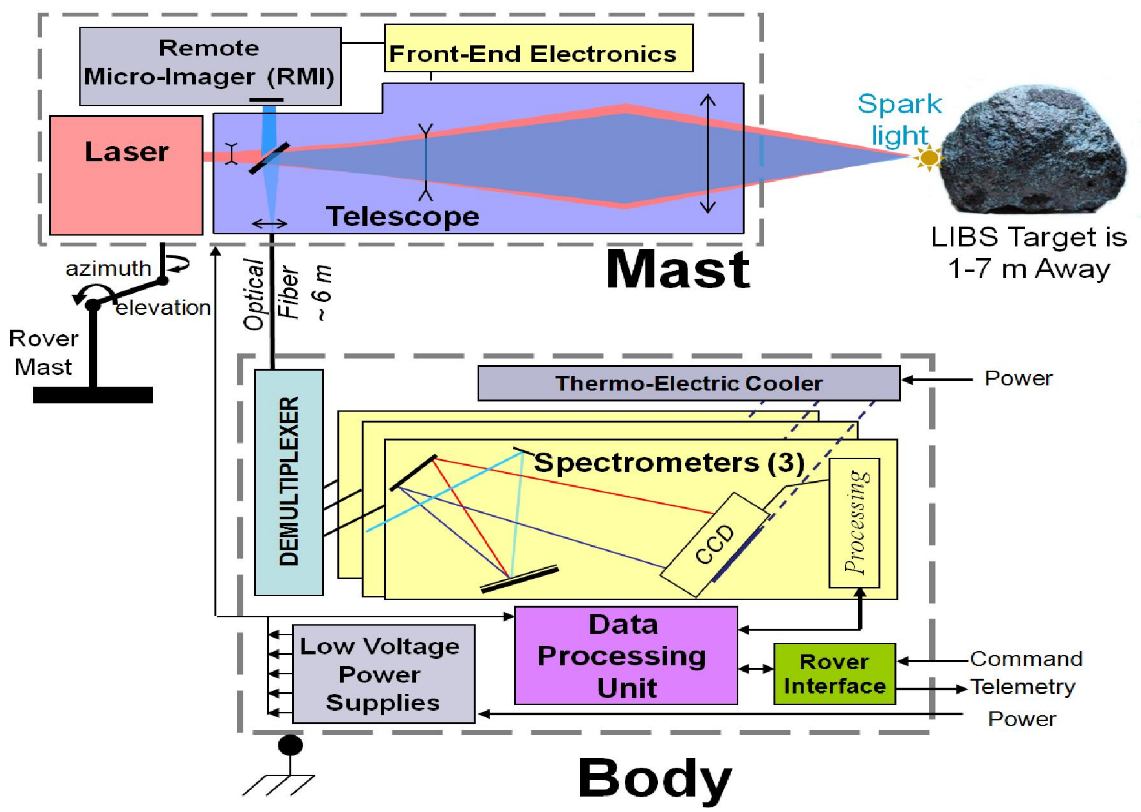

Figure 16. Block diagram of the ChemCam suite showing separate body-mounted and mast-mounted units.

4.2.7 Calibrations, Data, and Operations

Calibration of the LIBS data involves preflight calibrations, postlanding calibrations using the onboard targets, and comparisons with spectra obtained on Mars analogs in terrestrial laboratories. Preflight calibration targets consist of approximately seventy standards, two-thirds of which are igneous standards covering a somewhat larger range of SiO_2 abundances than basalts and andesites. The preflight standards also include a range of "dirty" sulfates, and a number of sedimentary materials. "Dirty" standards that are mixtures of materials are preferred over pure minerals, as pure mineral compositions can be easily determined by the occurrence of only the elements present in the given mineral. Postlanding calibrations will be done with the onboard standards described above, and by comparison with both the preflight calibrations and with Mars analog samples analyzed in terrestrial LIBS laboratories. Comparisons between ChemCam LIBS spectra and LIBS spectra from terrestrial laboratories need to be studied, as does the effect of distance on calibrations. For example, different emission lines respond to distance differently likely based on their activation energies. We are actively studying these effects, and we expect to continue these studies into the mission phase.

Operation of the instrument is expected to be shared 50/50 between the U.S. and France. After transition to remote operations, the team will operate on a 38 day cycle during which the Mars time shifts relative to Earth time. The French team will be responsible for instrument operation during the half of the cycle in which downlinks are too late in the day in the US, while the U.S. team members will operate the instrument during times when downlinks are too late in the day in France. Staffing of science theme groups will be done by both countries regardless of who has instrument operation responsibilities at any given time, so that scientists from both countries are involved in decisions at all times.

The science team Co-Investigators are listed in Table 4. Team members are expected to help staff the Science Operations Working Group and ChemCam Payload Downlink Lead positions, especially given the expected frequent operation of the instrument. RMI data reduction will use JPL imaging tools. LIBS data reduction will consist of preprocessing such as background subtraction, wavelength calibration, and distance corrections. Data processing will use multivariate analysis techniques, relying heavily on comparison with spectra of high-fidelity Mars analogs analyzed in terrestrial laboratories. We envision using principal components analyses (PCA) and related techniques to classify and compare samples, while we expect to use partial least squares (PLS) to calibrate and quantitatively determine elemental compositions (e.g., Clegg et al., 2009). Payload Downlink Leads will be expected to carry out preprocessing and sample classification in order to present results to the SOWG for tactical use.

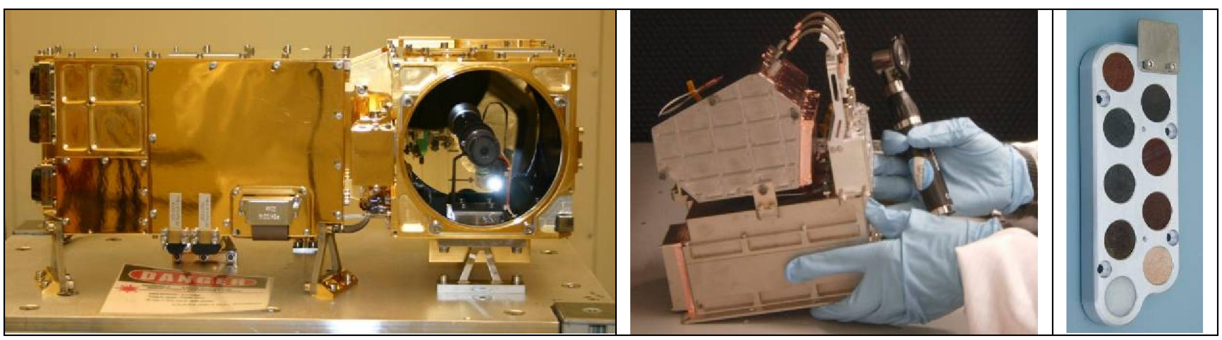

Figure 17. Engineering Qualification Model Mast Unit, Engineering Model Body Unit, and Engineering Model rover-mounted calibration targets. Photo credits: LANL and JPL.

Table 4. ChemCam PI and Co-Investigators

Team Member	Expertise or Role	Institution
Roger Wiens	Principal Investigator	Los Alamos National Lab
Sylvestre Maurice	Deputy Principal Investigator	IRAP, France
Diana Blaney	Investigation Scientist	JPL
Nathan Bridges	Imaging, geomorphology	JPL
Benton Clark	Geochemistry	Lockheed Martin, Denver
Sam Clegg	LIBS technique	Los Alamos National Lab
David Cremers	LIBS technique	Applied Research Associates, Inc.
Lionel d'Uston	Geochemistry	IRAP, France
Ken Herkenhoff	Imaging, geomorphology	USGS, Flagstaff
Laurel Kirkland	Spectroscopy	LPI, Houston
Yves Langevin	Imaging, geomorphology	IAS, Univ. Paris Sud-XI
Nicolas Mangold	Geomorphology	LPGN, Univ. Nantes
Gerard Manhes	Geochemistry	IPG, Paris
Patrick Mauchien	LIBS technique	CEA, Saclay
Christopher McKay	Exobiology	NASA Ames
Horton Newsom	Geochemistry	Univ. New Mexico
Franck Poitrasson	Geochemistry	GET, France
Violaine Sautter	Geochemistry	LMCM, France
David Vaniman	Geochemistry	Los Alamos Nat'l Lab.

4.3 CheMin (Chemistry and Mineralogy)

4.3.1 Contributions of CheMin to MSL Science Objectives

An important science goal of the MSL mission is to identify and characterize past or present habitable environments as recorded in sediments and rocks. CheMin is a definitive mineralogy instrument that will identify and quantify the minerals present in rocks and soil delivered to it by the Sample Acquisition, Sample Processing and Handling (SA/SPaH) system. By determining the mineralogy of rocks and soils, CheMin will assess the involvement of water in their formation, deposition, or alteration. In addition, CheMin data will be useful in the search for potential mineral biosignatures, energy sources for life or indicators of past habitable environments. CheMin can unequivocally identify and quantify minerals above its detection limits in complex natural samples such as basalts, multicomponent evaporite systems, and soils.

4.3.2 Instrument Description

CheMin, short for "Chemistry and Mineralogy," is a powder X-ray Diffraction (XRD) instrument that also has X-ray Fluorescence (XRF) capabilities. CheMin is part of the Analytical Laboratory of the MSL rover, which is located inside the main body of the rover. CheMin will analyze as many as 74 samples delivered by the SA/SPaH system during the nominal prime mission, but is capable of analyzing many more because its sample cells can be reused for additional analyses. Each analysis may take up to 10 hours of analysis time, spread out over two or more Martian nights, although some samples may provide acceptable results in a single sol. CheMin utilizes a microfocus cobalt X-ray source, a transmission sample cell, and an energy-discriminating X-ray sensitive CCD to produce simultaneous 2-D X-ray diffraction patterns and energy-dispersive histograms from powdered samples. Raw CCD frames are processed into data products onboard the rover to reduce the data volume. These data products are transmitted to Earth for further processing and analyses.

4.3.3 Measurement Description

In operation, a collimated X-ray beam from the X-ray tube is directed through a transmission sample cell containing powdered material prepared and delivered by the SA/SPaH system. An X-ray sensitive CCD imager is positioned on the opposite side of the sample from the source and directly detects X-rays diffracted or fluoresced by the sample. The CCD detector is operated in single-photon counting mode (the detector is read out at a frequency that ensures that the vast majority of pixels contain charge from either zero or one photon). The CCD detector is exposed to the X-ray flux, read out and erased a large number of times for each analysis (1000 or more exposures). When operated in this manner, the CCD can be used to measure the charge generated by each photon (and hence its energy). Diffracted X-rays strike the detector and are identified by their energy, producing a two-dimensional image that constitutes the diffraction pattern. All of the X-rays detected by the CCD are summed into a histogram of number of photons vs. photon energy that constitutes an energy-dispersive X-ray histogram of the sample. A cartoon of the CheMin geometry is shown in Figure 18 below. At incremental radii the two-dimensional pattern is summed circumferentially about the central undiffracted beam (ground processing) to yield a one-dimensional 2θ plot comparable to conventional diffractometer data. Quantitative mineralogical results are obtained from XRD data by Rietveld refinement, FULLPAT and other full-pattern fitting techniques. Both crystalline and amorphous materials can be analyzed in this fashion.

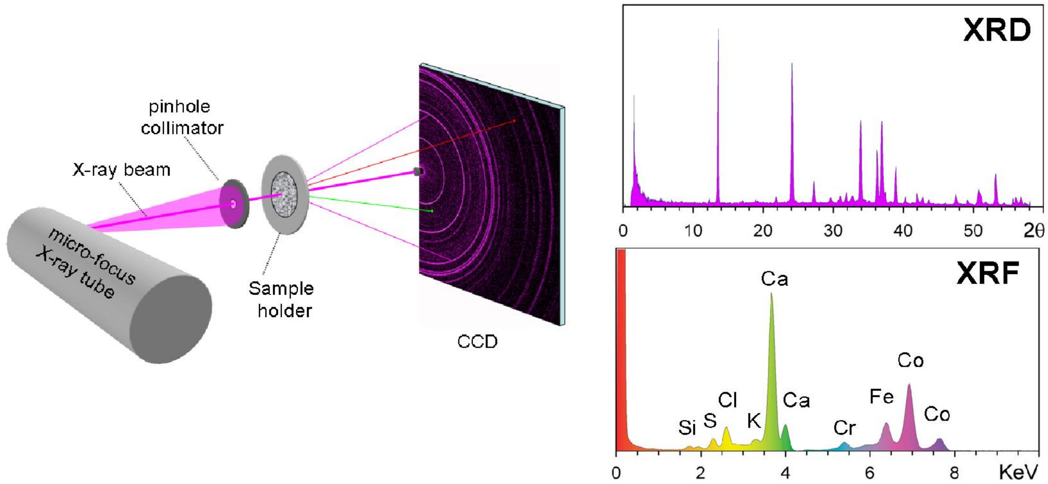

Figure 18. Geometry of the CheMin instrument. (left) Overall geometry of CheMin; (above right) XRD 2θ plot obtained by summing diffracted photons from either of the characteristic lines of the X-ray source, Co Kα or Co Kβ (Co Kα is shown, colored magenta); (below right) X-ray energy-dispersive histogram obtained by summing all of the X-ray photons detected by the CCD (fluoresced photons from the sample shown schematically for elements Fe and lighter).

4.3.4 CheMin Science Requirements

The original Project-level science requirements statement is: "The Project System will be able to utilize the X-ray diffraction (XRD) and X-ray fluorescence (XRF) capabilities of CheMin to establish the mineralogy and elemental composition of rocks and soils, inferring the formation and alteration histories of samples acquired by the mission." This requirement was amended when the Si-PIN diode for reflection-geometry XRF was descoped from the proposed design. Quantitative XRF analysis of elemental composition is now only a "best effort" task dependent on progress in element quantification using only the transmission geometry. The critical components of the initial requirement are still supported, because CheMin will still use the CCD energy-dispersive histogram capability to aid in mineral identification and analysis. Specific measurement objectives are as follows:

XRD detection limits. The CheMin instrument shall be able to detect individual minerals in complex mixtures that are present at the 3% level and above.

XRD accuracy. For minerals that are present in concentrations of 12% and above (4 times the minimum detection level, 4 × MDL), the goal is for CheMin to be able to state the absolute amount present ± 15%. For example, a mineral present in 12% concentration shall be quantifiable as 12% ± 1.8%. Reaching the goals for accuracy and precision will depend on whether the grain flow in the cell during measurement can be improved.

XRD precision. The goal from precision of a reported mineral concentration, when present in quantities greater than 4 × MDL, is ± 10%.

XRF detection limits, accuracy and precision. As stated above, XRF requirements have been descoped from the instrument, and are now on a "best efforts" basis. CheMin will return XRF data in the form of energy-dispersive X-ray histograms with a Full Width Half Maximum

(FWHM) of 250 eV or better measured at the position of Fe Kα (6.4 keV). As a result of the transmission geometry and the presence of a Mylar or Kapton window between the sample and the detector, CheMin will only detect elements with an atomic number greater than 12 (Mg) in the periodic table.

4.3.5 CheMin Instrument Operation

The CheMin sample handling system consists of a funnel, a sample wheel (which carries 27 reusable sample cells and 5 permanent reference standards), and a sample sump where material is dumped after analysis (Figure 19). CheMin receives drill powders or scoop samples from the SA/SPaH (Sample Acquisition/Sample Processing and Handling) system, through the drill, scoop, and CHIMRA sorting assembly. A maximum of 65 mm^3 of sample material is delivered to the piezoelectrically vibrated funnel system that penetrates through the rover deck (during the time period when CheMin is not receiving samples, the CheMin inlet is protected by a cover). The funnel contains a 1 mm mesh screen to keep larger than expected grains from entering the CheMin sample handling system. Grains that cannot pass through the screen will remain there for the duration of the mission (samples will have been prescreened first to 1 mm and then to 150 μm in the CHIMRA sorting chamber, to prevent clogging of the CheMin funnel screen). Any grains between 1.0 mm and 150 μm that pass through the screen will pass into the upper reservoir portion of the sample cell, where they will remain until the cell is inverted and they are dumped into the sump. However, under nominal conditions, the CheMin funnel will only receive material that has passed through the CHIMRA's 150 μm sieve. For the lifetime of the mission, nominally one Mars year, CheMin is required to accept and analyze material delivered from SA/SPaH with no more than 5% CheMin internal contamination between samples. Self-generated contamination originates from material that has remained in the funnel from previously delivered samples (and delivered along with subsequent samples), or from material that has remained in previously used analysis cells (CheMin will nominally use each reusable cell two to three times to accommodate 74 analyses during the mission). CheMin empties used sample cells by inverting and vibrating the cell and over a sump inside the instrument. CheMin may reduce contamination by sample dilution – aliquots of sample material can either be dumped into the funnel and delivered directly to the sump through a shunt in the wheel without entering a sample cell (to remove funnel contamination), or a previously used sample cell can be filled, shaken and emptied to the sump prior to receiving an aliquot of sample for analysis (to remove sample cell contamination). These processes will require coordination with SA/SPaH to deliver more than one aliquot of a given sample.

A full and complete analysis of an individual sample is called a "major frame" and may require as much as 10 hours of analysis time, at separate times over multiple sols, although some samples will not require such long analysis time and may provide adequate data within a few hours during a single sol. Analyses will be made at night when the CCD can be adequately cooled. Once a major frame of data is sent to ground and accepted, the analyzed material is emptied from the cell and that cell is ready to be reused. CheMin does not have the capability to store previously analyzed samples for later reanalysis.

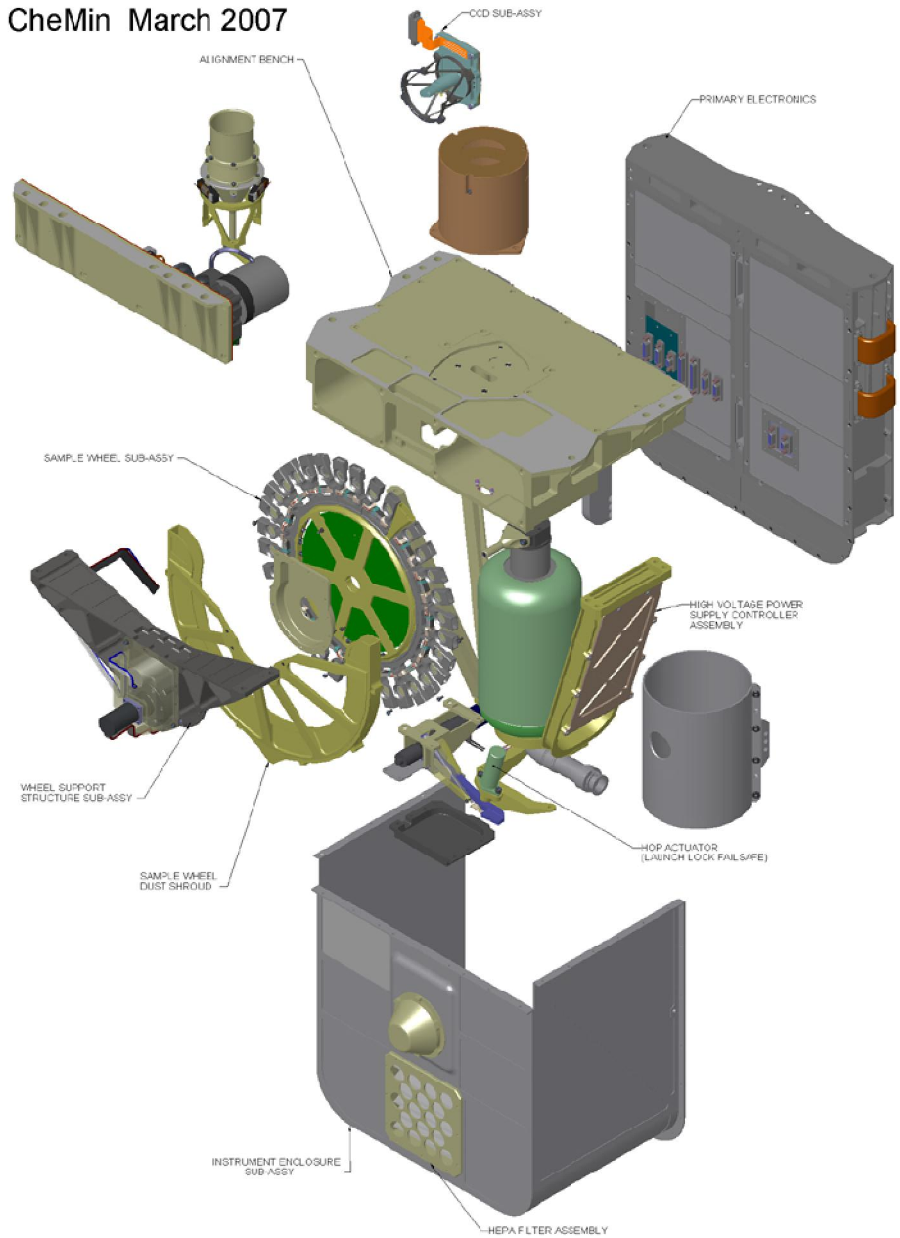

Figure 19. Exploded view of CheMin components.

4.3.6 The Sample Cells and Sample Wheel

The collimated ~50 µm diameter X-ray beam illuminates the center of an 8 mm diameter, 175 µm thick sample cell bounded by 6 µm thick Mylar or somewhat thicker Kapton windows. The sample introduced into the funnel consists of ≤ 65 mm^3 of powdered material with a grain size of <150 µm. Only about 10 mm^3 of material is required to fill the sample cell, which is a disc-shaped volume with an 8 mm diameter and 175 µm thickness. The remaining sample material occupies a reservoir above the cell (see Figure 20). During filling, analysis, and dumping, the sample cell is shaken by piezoelectric actuators (piezos). The modes in which the piezos will be driven are still under test and may vary from sample to sample, depending on such things as grain cohesion (e.g., clay-rich samples versus samples that lack fine particles). Testbeds have used modes in which samples have been vibrated at sonic frequencies (900-2230 Hz). Frequency of the piezo-actuator has been ramped in testbeds so that during a part of the cycle the sample-piezo system is at resonance, at which time the sample exhibits bulk convective movement similar to a liquid, delivering sample grains in random orientation into the volume irradiated by the beam. A nominal resonant frequency of 2150 Hz is characteristic of the tuning forks designed for the MSL CheMin. During the moderate shaking which results in grain convection, it is possible that phase segregation will occur as a result of size or density differences between individual mineral grains. To reduce this problem CheMin can, at intervals depending on the cycle of each individual frame, use episodically larger shaking amplitudes (i.e., “chaos mode”) to homogenize particle size or density segregations in the sample chamber.

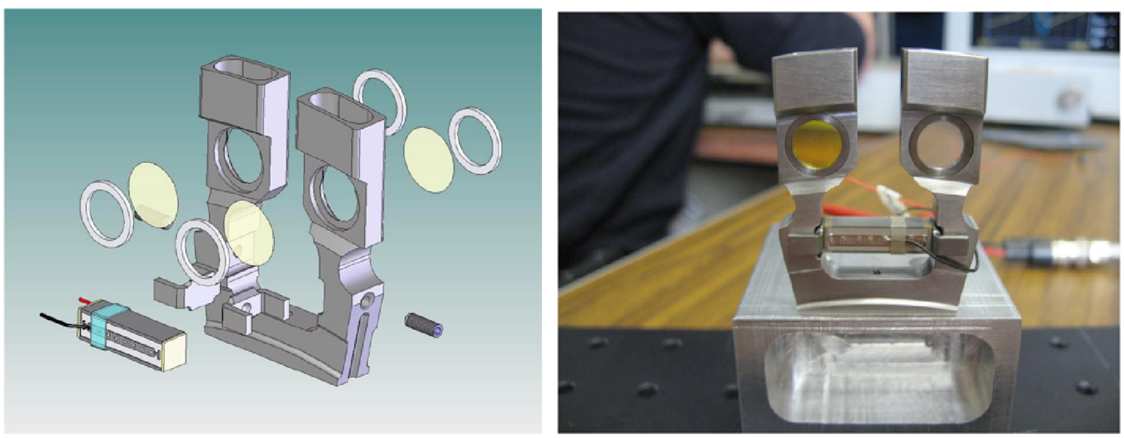

Figure 20. Illustration of CheMin dual-cell geometry. (left) Exploded view of dual-cell assembly showing windows, tuning-fork assembly, and piezodriver. (right) Assembled cell, ready for testing in testbed (yellow Kapton window on left, clear Mylar window on right).

The CheMin sample cells are constructed in dual-cell “tuning-fork” assemblies with a single horizontally driven piezoelectric actuator in each assembly (Figure 20). A bypass cell allows purge samples to be used to remove prior sample contamination from the inlet funnel; the purge samples are moved directly to the sump after passing through the funnel. Sixteen of the dual-cell assemblies are mounted around the circumference of the sample wheel (Figure 21). Five of the cells will be devoted to carrying standards; the other 27 cells are available for sample analysis and may be reused by dumping samples into the sump after analysis.

Both Mylar- and Kapton-window cells are mounted on the wheel. The two window types have different advantages and weaknesses. Mylar windows have a very flat diffraction background but Mylar is less durable than Kapton under severe vibration and is susceptible to destruction if highly acidic samples (e.g., copiapite) are loaded. Kapton windows are extremely durable under severe vibration and are not susceptible to acid attack, but have a small diffraction contribution at ~6-7° 2θ which could interfere with the (001) diffraction peak from some clay minerals. Windows of both Kapton (in 13 cells) and Mylar (in 14 cells) are used in the Flight Model (FM) and Development Model (DM), as shown in Figure 21. Most of the standard cells use Kapton, but the amphibole standard uses a Mylar window.

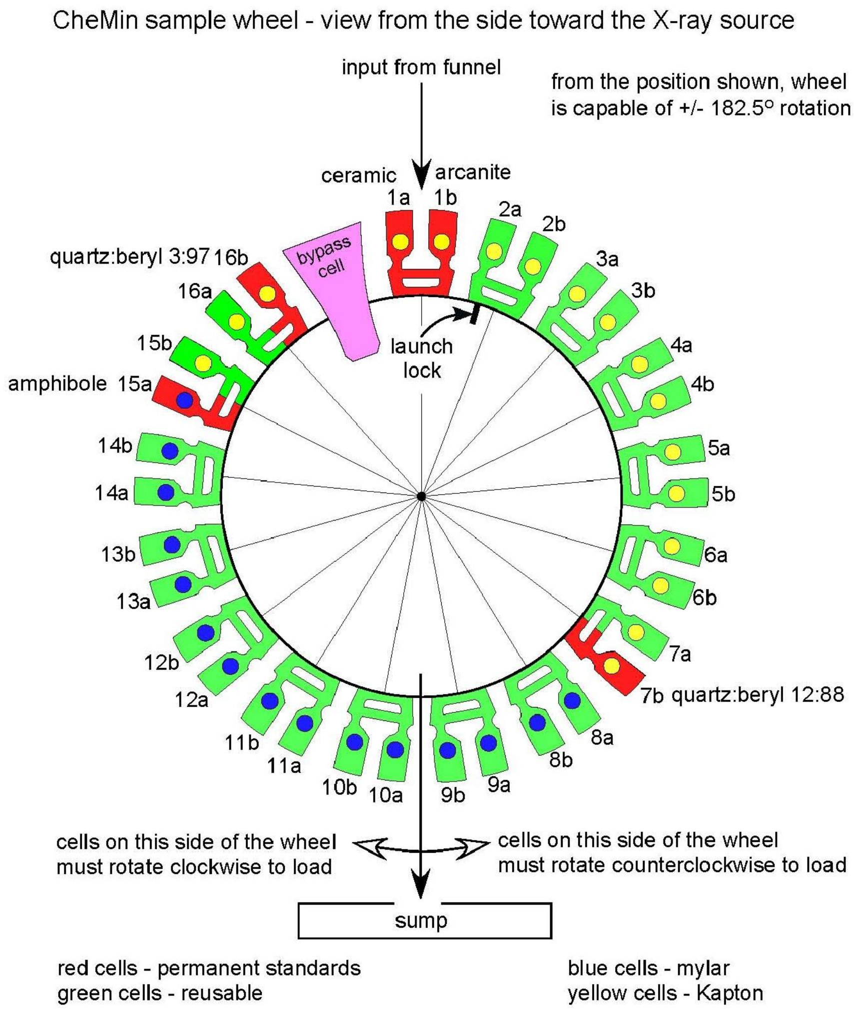

Figure 21. Schematic diagram of the CheMin sample wheel.

4.3.7 Detection of X-ray Photons by the CCD

CheMin will use a 600 × 600 E2V CCD-224 frame transfer imager operated with a 600 × 582 data collection area. The pixels in the array are 40 × 40 μm^2, and the active region of deep depleted silicon is 50 µm thick. The front surface passivation layer is thinned over a substantial fraction of the active pixel area. This imager is a modern version of the E2V CCD-22 that was specially built for an X-ray astronomy application. The large size of the individual pixels causes a greater percentage of X-ray photons to dissipate their charge inside a single pixel rather than splitting the charge between pixels. The enhanced deep depletion zone results in improved charge collection efficiency for high energy X-rays. The thin passivation layer makes the CCD sensitive to relatively low-energy X-rays.

In order to keep the CCD from being exposed to photons in the visible energy range (from X-ray induced optical fluorescence) during analysis, a 150 nm Al film supported on a ~2,000 Å polyimide film is placed in front of the detector. The detector itself is cooled to a target temperature of minus 60 °C, but the actual CCD temperature will depend on the rover body upper-surface temperature. By cooling the CCD, dark current is eliminated, and the effects of damage to the silicon lattice by neutrons from the Radioisotope Thermoelectric Generator (RTG) and the DAN science instrument will be reduced. Should the temperature not reach minus 60 °C for the analysis, the dark current will increase and the neutron damage to the CCD will begin to adversely affect Charge Transfer Efficiency (CTE), resulting in higher background counts and increased full width half maximum (FWHM) in X-ray peaks.

4.3.8 X-ray Diffraction Mode

The CCD is placed in the forward-scattered direction relative to the X-ray beam so that mineral phases with large interplanar spacings (and hence narrow diffraction cones of low 2θ), such as layer silicates, can be detected. In addition, low-index lines (which are commonly the strongest and most definitive for phase identification) lie in the forward-scattered direction. Table 5 shows the expected 2θ range (for Co Kα radiation) and 2θ FWHM for X-ray diffraction.

Table 5. Critical source and detector requirements

Parameter	Source and Detector Characteristics
2θ range	5-50° 2θ
2θ resolution	≤0.35° 2θ
Operating voltage	28 keV
Measured flux (sample dependent)	~250 counts/second
CCD energy range	1-25 keV
CCD energy resolution @6.93 keV	≤250 eV

4.3.9 Energy-Dispersive Mode: Focus on Characteristic Cobalt Radiation

The CCD-224 directly detects individual X-ray photons that are absorbed by the active silicon, producing a number of electron hole pairs equal to the energy of the X-ray in electron volts, divided by 3.65 (the energy of an electron-hole pair in the silicon lattice). For example, a cobalt Kα X-ray with an energy of 6.93 keV will produce 1,899 electron hole pairs. Single pixel events (those representing the absorption of a single photon into a single pixel of the CCD) are summed into a histogram of energy vs. number of counts. This histogram constitutes the energy-dispersive fluorescence spectrum of the sample. Table 5 shows the energy range and resolution.

In its originally proposed configuration, the CheMin geometry was optimized for sample chemical analysis based on energy-dispersive analysis of the fluorescence photons. For this purpose a fluorescence detector was mounted on the tube side of the sample cell, in a reflection geometry similar to that of other instruments (e.g., APXS) where traditional X-ray fluorescence chemical analyses can be obtained by use of fundamental parameters methods. The descope of the reflection geometry detector from the MSL CheMin has removed this capability. However, energy-dispersive capability is still required for discriminating diffracted photons of a specified energy (e.g., Co Kα, 6.93 keV) from fluoresced photons (e.g., Fe Kα , 6.40 keV) or diffracted photons of other energies (e.g., Co Kβ, 7.65 keV). Although of secondary importance to the energy resolution of primary Co X-rays, qualitative chemical information from secondary X-rays will also be important for supporting mineral identification by pinpointing the chemical constituents to be included or excluded in mineral search/match routines. Future "best effort" characterization, studies may ultimately permit quantification of chemical composition by Monte Carlo methods.

4.3.10 Modes of X-ray Photon Detection for X-Ray Diffraction

A special case of X-ray detection by the CCD is the detection of either Co Kα or Co Kβ characteristic photons from the primary source. When Co Kα (or Co Kβ) photons are detected, the X,Y pixel location in the CCD is identified and the corresponding X,Y location in a 600 × 582 counting number array is incremented by one. This process results in a Co Kα (or Co Kβ) diffraction image. Various strategies are used in onboard data processing to optimize the quality or quantity of diffraction data returned (e.g., "single pixel" detection, and "split pixel" detection).

An additional 600 × 582 array stores an image of all of the photons detected by the CCD regardless of energy. This array acts very much like a piece of photographic film, recording the XRD pattern as well as background, energy-dispersive data, and Bremsstrahlung.

4.3.11 Calibration Standards

Five permanent cells, in both the FM that goes to Mars and the DM that stays here on Earth, will be loaded with calibration standards as shown in Figure 21. Three of these cells will be loaded with single minerals or a synthetic ceramic and two will be loaded with differing quartz/beryl mixtures. The FM will be loaded with the same five permanent standards as the DM; otherwise the FM will not be exposed to any other materials in open cells before samples are acquired on Mars. The five permanent standards in the DM and FM will be used for cross calibration of the DM following FM calibration.

Basic calibration, completed prior to delivery of the instrument to MSL Assembly, Test, and Launch Operations (ATLO), is performed using only the five permanent standards loaded into the sample cells of the FM. Calibration of these standards will include measurement of 2θ range and 2θ FWHM for XRD, and of the required energy range and FWHM for elemental peaks, in particular Fe Kα, Co Kα, and Co Kβ.

4.3.12 Quantitative XRD calibration of the Development Model and other CheMin Testbeds

Quantitative X-ray diffraction (QXRD) calibration will be performed using the DM and various testbeds. For QXRD calibration, synthetic mineral mixtures that mimic real samples likely to be encountered on Mars will be carefully prepared from minerals mixed in controlled weight proportions.

For characterization of CheMin operation across a broad spectrum of samples, synthetic and natural, the DM will be supported by a number of testbeds and facilities that replicate various parts of the DM/FM function with varying levels of fidelity. These testbeds and facilities are listed below:

The Development Model (DM): The DM will be set up in a testbed configuration at JPL in CheMin Co-I Albert Yen's laboratory. Prior to launch, the DM will be used to test algorithms, establish calibrations, develop operation scenarios, and characterize Mars analog samples. During landed operations the DM unit will be used to test new sequences, develop operation scenarios, and characterize Mars analog samples.

Analytical facility for Mars analog rocks: This facility at NASA Ames Research Center (ARC) will house several CheMin MSL analog instruments. The principal instruments in this laboratory are an Inel™ X-ray diffractometer, a CheMin IV instrument (Bish et al., 2007), and a Terra instrument (a field-deployable instrument developed by InXitu, Inc. (Blake et al., 2008)). These instruments will be used to analyze Mars analog rocks in a geometry similar to the CheMin FM and the DM instruments. The Inel™ X-ray diffractometer is configured to analyze Mars analog rocks in a geometry similar to the CheMin flight instrument but with a very different detector. This instrument is equipped with a Co tube and a 120° parallel detection system capable of collecting XRD patterns with resolutions in excess of the spacecraft instrument (but which can be degraded to MSL CheMin resolution for comparison and pattern matching). A Mars sample chamber is installed with a carousel and MSL funnel, and a CheMin transmission sample cell capable of being filled, piezoelectrically shaken during analysis and dumped, all under Mars pressure. A large number of patterns of Mars analog rocks and soil will be collected for analysis prior to, during and after the prime MSL mission. The CheMin IV and Terra instruments have the resolution and diffraction geometry of the MSL Flight instrument and will be used in supporting tests.

CheMin IV testbeds: In addition to the CheMin IV at NASA ARC, three additional CheMin IV testbeds will be established at Co-I facilities, including: JPL (Co-I Albert Yen), Indiana University (Co-I Dave Bish), and NASA Johnson Space Center (Co-Is Doug Ming and Dick Morris). These CheMin IV testbeds will be used to screen samples that are candidates for analysis in the DM.

4.3.13 Calibration of the Flight Model in Mars Operations

In use on Mars, two standards will be analyzed as soon as possible after landing but after analysis of a first contingency sample. The standards to be analyzed are pure amphibole (for energy dispersive histogram calibration) and 97% beryl (for XRD calibration). Subsequent calibrations will be performed using one or more of the permanent standards on a nominal schedule of once every 40 sols.

4.3.14 Science Team Member List

The CheMin science team presently includes:

- David Blake (CheMin PI), NASA Ames Research Center
- David Vaniman (CheMin Deputy PI), Los Alamos National Laboratory
- Robert Anderson, Jet Propulsion Laboratory
- David Bish, Indiana University
- Steve Chipera, Chesapeake Energy
- Joy Crisp, Jet Propulsion Laboratory
- David Des Marais, NASA Ames Research Center
- Bob Downs, University of Arizona
- Jack Farmer, Arizona State University
- Sabrina Feldman, Jet Propulsion Laboratory
- Marc Gailhanou, CNRS, France
- David Joy, University of Tennessee
- Doug Ming, NASA Johnson Space Center
- Dick Morris, NASA Johnson Space Center
- Philippe Sarrazin, inXitu, Inc.
- Ed Stolper, California Institute of Technology
- Allan Treiman, Lunar and Planetary Institute
- Albert Yen (Co-I and CheMin Investigation Scientist), Jet Propulsion Laboratory

4.3.15 CheMin Instrument Modes

CheMin will perform integrations in one of two modes. In "calibration mode," CheMin measures one of five sample cells that contain reference standards in order to calibrate the positions and intensities of peaks in the diffraction pattern and the energy-dispersive histogram. In "sample mode," CheMin measures material delivered by SA/SPaH and commands can specify integration times as appropriate. In the nominal case, a single < 65 mm^3 aliquot of sample material is delivered to a sample cell and an analysis is initiated. In cases where contamination from previous sample material is suspected either in the funnel or in a previously used sample cell, contamination can be reduced by sample dilution. Contamination reduction in the funnel is accomplished through the use of a sample shunt on the sample wheel. The sample wheel is rotated to the shunt position and the < 65 mm^3 sample is dumped into the funnel during shaking. Sample material incorporates the funnel contamination as it transits through the funnel into the sample shunt. Following this, the shunt is rotated into the "dump" position and the shunt material is deposited in the sump. Contamination reduction in a previously used sample cell is accomplished by filling the cell, vibrating the cell for approximately 10 minutes and dumping the material. A second aliquot of material is delivered to the cell, vibrated for ~10 minutes and dumped. A third aliquot of material is delivered to the cell, and analyzed in the usual way.

During a nominal 10-hour analysis, CheMin collects and stores X-ray data as individual 600 × 582 pixel CCD images of 5-30 seconds exposure each. A "minor frame" nominally consists of ½ hour of these images, or 60-360 frames depending on integration time. A 10 hour analysis of a sample, for example, typically comprises 20 such minor frames and is called a "major frame."

There is insufficient bandwidth to deliver all of CheMin's raw data to Earth. When commanded, CheMin delivers raw data to the Rover Compute Element (RCE) which in turn partially processes the raw data for each minor frame, in order to reduce the data volume. Each minor frame of data transmitted to Earth contains one or more raw frames in order to assess the health of the detector, a variety of engineering and health information about the instrument, and one or more of four possible processed data products. The four types of data products are described below:

1. In "fully processed mode," each image is reduced to a pixel map containing ones and zeros, where "1" represents the detection of a photon within ground-specified high and low energy limits (e.g., Co-Kα) , and "0" represents everything else. Each pixel map is summed into a 600 × 582 counting number array of pixel positions; the result is a 2-D energy-filtered diffraction pattern.
2. In addition to the energy-filtered diffraction pattern, "fully processed mode" also provides a histogram made of all of the photons detected vs. energy, which amounts to an X-ray energy-dispersive spectrum of the sample material.
3. In "film" mode, images are summed into a 600 × 582 array as raw data. A single real number array holds the summed images for each minor frame.
4. In "modified raw" mode, pixels below a selected threshold are set to zero, and data that are above that threshold are compressed with x, y, and intensity information preserved.

Procedures for the processing and analysis of CheMin data on the ground can be broken down into the following steps:

<u>Preparation of raw data</u>. All downlinked raw, modified raw, film mode, or fully processed mode data are evaluated to check CheMin integration performance, background and/or data processing.

<u>Preliminary analysis of XRD data.</u> Data are processed to create 1-D 2θ plots. Patterns are compared with the ICDD (International Centre for Diffraction Data) powder diffraction file to determine major mineral components.

<u>Products furnished to MSL Science Operations Working Group (SOWG) in tactical time frame.</u> Preliminary data are provided as diffractograms in JPEG format as 1-D 2θ plots. The CheMin Payload Downlink Lead generates Level 2 data products from the downlinked data and shares them with the SOWG. CheMin Science Team members offer preliminary identifications of any major or clearly discernable mineral components during this tactical cycle. Periodically these data will support a "drive away" or "stay" decision for rover operations.

<u>Analysis refinement for products provided in strategic time frame.</u> Rietveld computational refinement methods will be utilized to deconvolute composite spectra into spectra of individual minerals. These spectra will be compared with library spectra to identify mineral components and to derive quantitative mineral abundances.

4.4 DAN (Dynamic Albedo of Neutrons)

The Dynamic Albedo of Neutrons (DAN) is an active/passive neutron spectrometer that measures the abundance and depth distribution of H- and OH-bearing materials (e.g., adsorbed water, hydrated minerals) in a shallow layer (~1 m) of Mars' subsurface along the path of the MSL rover. In active mode, DAN measures the time decay curve (the "dynamic albedo") of the neutron flux from the subsurface induced by its pulsing 14 MeV neutron source (Figure 22 shows an example). A detailed description of the DAN instrument and scientific investigation can be found in Litvak et al. (2008). The experiment is contributed by the Federal Space Agency of Russia.

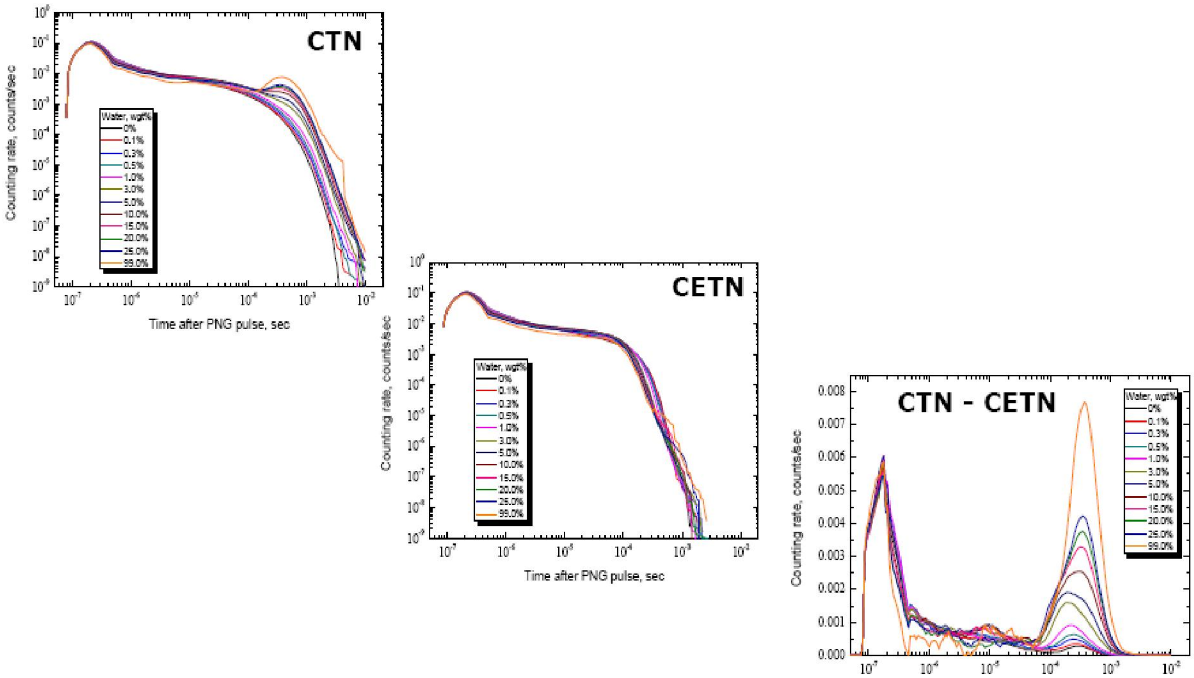

Figure 22. Numerical simulations of the neutron count rate versus time (i.e., die-away curve) for the unshielded (left) and shielded (middle) detectors as a function of water abundance. The right panel shows the difference between the two count rates.

The science objectives of the DAN instrument are as follows: 1) Detect and provide a quantitative estimation of the hydrogen in the subsurface throughout the surface mission; 2) Investigate the upper <0.5 m of the subsurface and determine the possible layering structure of hydrogen-bearing materials in the subsurface; 3) Track the variability of hydrogen content in the upper soil layer (~1 m) during the mission by periodic analysis; and 4) Track the variability of neutron radiation background (neutrons with energy < 100 keV) during the mission by periodic analysis.

The DAN instrument is expected to be used during rover traverses (e.g., during short stops at ~1 m intervals) and while the rover is parked. Short-duration (< 2 min) measurements will provide a rough estimate of the water-equivalent hydrogen distribution with an accuracy of

~1% by weight. Longer-duration (~30 min) measurements are necessary to derive the vertical distribution of water-equivalent hydrogen with an accuracy of 0.1-0.3% by weight.

The DAN PI and Co-Investigators are listed in Table 6.

Table 6. DAN science team members

Igor G. Mitrofanov, PI	Space Research Institute
Maxim Litvak, Co-I, Deputy PI	Space Research Institute
Alexandre S. Kozyrev, Co-I	Space Research Institute
Anton B. Sanin, Co-I	Space Research Institute
Alberto Behar, Co-I	Jet Propulsion Laboratory
Bill Boynton, Co-I	University of Arizona

4.5 MAHLI (Mars Hand Lens Imager)

4.5.1 Introduction

The Mars Hand Lens Imager (MAHLI) is a focusable color camera located on the turret at the end of the MSL robotic arm. The instrument acquires images of up to 1600 by 1200 pixels with a color quality equivalent to that of consumer digital cameras. Table 7 summarizes the basic characteristics of the instrument.

Table 7. MAHLI design characteristics (parameters to be verified on flight unit)

Parameter	Value/Description	
Focus	Adjustable; working distances 20.4 mm to ∞	
Focus group range of motion	11.44 mm	
Bandpass	380–680 nm	
Pixel scale	Variable from 13.9 µm/pixel to >>> 13.9 µm/pixel	
Focus-Position Dependent Parameters	25 mm working distance, 15 µm/pixel	∞ working distance
Depth of field	1.6 mm	> 4800 mm
Field of view	34.0° diagonal	39.4° diagonal
Focal ratio	f/9.8	f/8.5
Effective focal length	18.3 mm	21.3 mm
Back focal length	19.8 mm	8.4 mm

MAHLI images can be acquired at working distances between ~20.5 mm and infinity, permitting acquisition of closeup views with a pixel scale/spatial resolution as high as 13.9 µm per pixel, as well as selection of context views at greater working distances. Owing to likely uncertainties in robotic arm placement, the very highest resolution images might be challenging to obtain on Mars (we expect to learn more during testing of the arm placement capabilities prior to launch). Figure 23 shows an example image acquired by the flight MAHLI during pre-delivery testing. The ability to focus at infinity, combined with the location of the instrument on the MSL robotic arm, also permits imaging of some areas that are inaccessible to the other cameras on MSL, including in-focus views under the rover or—because the robotic arm can be raised to stand higher above the ground than the Remote Sensing Mast (RSM)—from a vantage point higher above the surface than that of the cameras on the RSM.

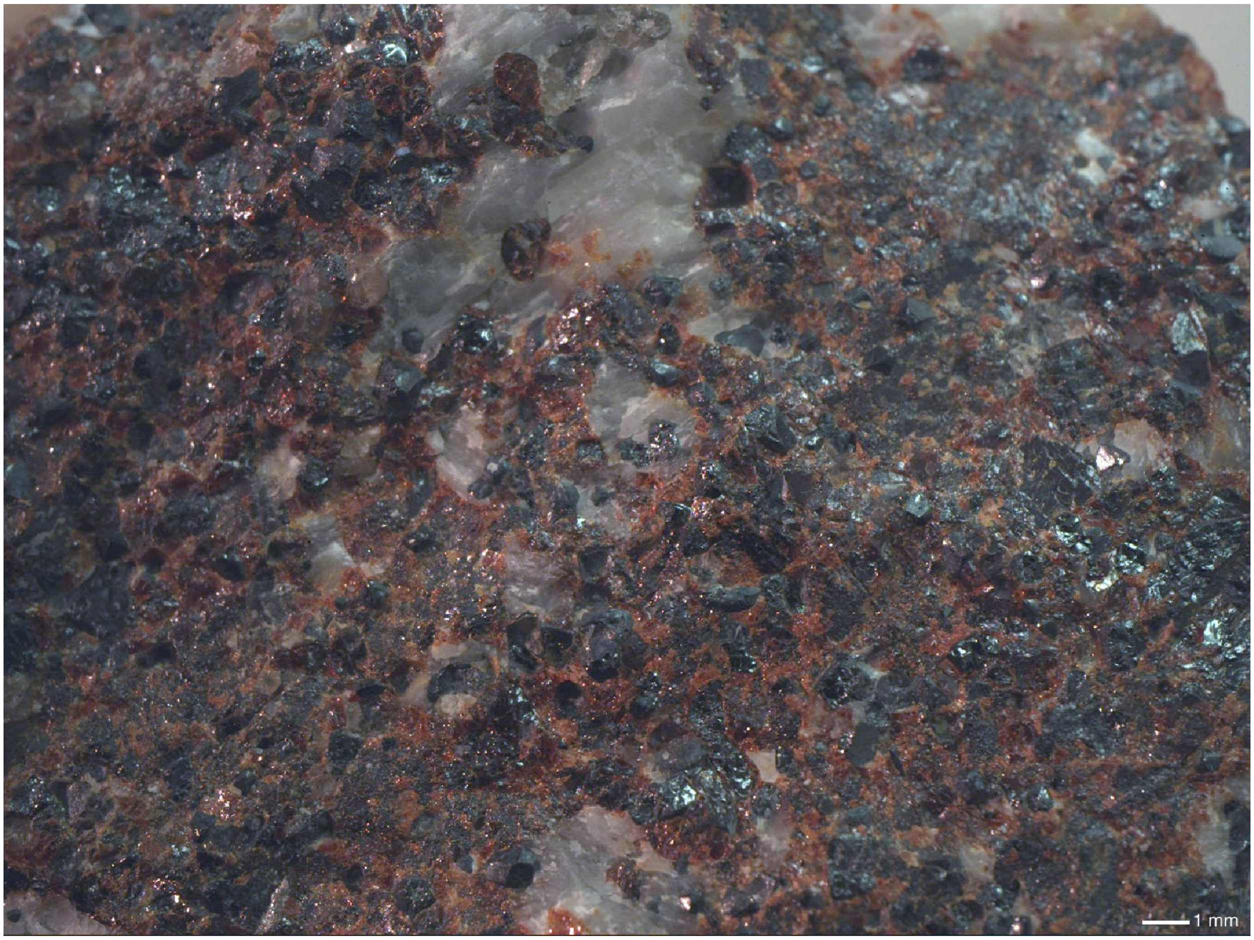

Figure 23. Flight MAHLI image of a zinc ore sample from Franklin, New Jersey, illustrating the color hand "hand lens" properties of the camera. Crystal shapes and colors are evident and light glints off of crystal faces. Note the 1 mm scale bar. The red mineral is zincite (ZnO_4).

4.5.2 Science

4.5.2.1 Goals and Objectives

The primary objective of the MAHLI investigation is to acquire images, particularly at (but not at all not limited to) hand lens scale, which facilitate the interpretation of the petrography and mineralogy of rocks and regolith fines at the MSL investigation site, attributes that are critical for describing the materials and deciphering the processes that have acted on them. Additionally, images from MAHLI will be used to help select materials to be sampled or examined by the other instruments (particularly APXS, CheMin, and SAM) and document the sampled or examined targets and collected materials.

4.5.2.2 Implementation

Color. Color imaging is achieved using a Bayer pattern filter, a common approach found in many consumer digital cameras. The luminance component of a resulting demosaiced image preserves the pixel-to-pixel geometric/spatial relations that one would see in a comparable single-band image.

Image Resolution. The MAHLI design permits imaging over a range of spatial scales between about 13.9 µm/pixel and infinity. Malin Space Science Systems follows a strict definition for resolution of in-focus images wherein the optical blur circle is equal to or less than one pixel across. Acquiring images with 13.9 µm per pixel under actual operational conditions on Mars will likely be challenged by as-yet unmeasured uncertainties in the ability to place the camera using the robotic arm.

Night Illumination. The MAHLI includes two sets of two white light LEDs to permit nighttime imaging. Each pair can be independently commanded on/off. MAHLI also has two ultraviolet (365 nm) LEDs to look for materials that fluoresce under longwave UV illumination. The UV LEDs are included on an exploratory, "best efforts" basis and are not a calibrated investigative tool. The MSL Project is required to accommodate night operations of MAHLI, but thermal and power constraints might preclude more than just occasional nighttime operation of the instrument and the robotic arm.

Focus and Autofocus. The MAHLI optics can be focused. An autofocus capability permits acquisition of in-focus images. Thus, MAHLI images can be in focus regardless of the exact positioning of the camera head by the rover's robotic arm.

Onboard Focus Stacking. Depending on the working distance and a target's surface relief, a close-focus view of a geologic target might not be in focus over the entire image. For those cases, MAHLI can be commanded to acquire a series of images taken at up to 8 focus positions that bracket the location of best focus. MAHLI can then be commanded to use onboard software to merge them into a single best-focus image (focal plane merge or "z-stack"). The MAHLI focus stacking algorithm also produces a range map of the target, providing a measure of the target's microtopography.

Camera Head Placement. The camera is positioned for imaging a target using the MSL robotic arm. A contact sensor, which has 2 "pokers" (a design similar to the 1 poker contact sensor used for the Mars Exploration Rover Microscopic Imagers) prevents the robotic arm from causing the MAHLI camera head, particularly its front optical element, to touch the target. The camera head may be placed by the robotic arm in positions that allow for nested (context) imaging of increasing spatial resolution (hence decreasing viewing area) as well as positioning for acquiring stereo pairs and mosaics.

Data Storage. Owing to the commonality in designs between the MSL MARDI, Mastcam, and MAHLI, and the requirements for considerable image storage space for the Mastcam and MARDI (which operates and stores data during MSL's descent to the Martian surface without interaction with the spacecraft), MAHLI has an 8 gigabyte nonvolatile NAND flash memory storage capability. The 8 gigabytes of storage is in addition to the camera's volatile 128 megabyte synchronous dynamic random access memory (SDRAM) buffer. This large data storage capability will permit acquisition of MAHLI images bracketed for exposure and robotic arm placement uncertainty; "thumbnail" images can be returned to Earth, examined, and then the best image of a given set of bracketed products can be requested for later return to Earth. The large data storage also means it is possible to store the data uncompressed, return the image in compressed form, and, if necessary, retrieve the image a second (or more) time with a different compression scheme.

Image Sub-Frames. To further provide users with the flexibility to consider image commanding trade-offs for a given downlink condition, images can be commanded at the full 1600 by 1200 pixel size, or as sub-frames with smaller pixel dimensions.

Video. Owing to the design commonality with the MARDI and Mastcams, the MAHLI can acquire 720p, ~7 Hz high definition video.

Science Team. The Mastcam, MAHLI, and MARDI investigations share a single science team (Table 8) which brings together persons with extensive terrestrial geoscience field expertise with people possessing considerable recent Mars rover and Mars camera development and operation experience.

Table 8. The Mastcam/MAHLI/MARDI science team

Name	Affiliation	Research Role
Kenneth S. Edgett	Malin Space Science Systems	MAHLI PI, sedimentology, stratigraphy
Michael C. Malin	Malin Space Science Systems	Mastcam and MARDI PI, geomorphology
James F. Bell III	Cornell University (moving to ASU in 2011)	Color properties, mineralogy/petrology
James Cameron	Lightstorm Entertainment	Videography, traverse science
William E. Dietrich	University of California, Berkeley	Geomorphology, hillslope processes
Lawrence J. Edwards	NASA Ames Research Center	Robotic vision, stereo, 3-D visualization
Bernard Hallet	University of Washington, Seattle	Cold climate geomorphology
Kenneth E. Herkenhoff	U.S. Geological Survey, Flagstaff	Rocks and regolith fines
Ezat Heydari	Jackson State University, Mississippi	Sediments and sedimentary rocks
Linda C. Kah	University of Tennessee, Knoxville	Sediments and sedimentary rocks
Mark T. Lemmon	Texas A&M University, College Station	Atmospheric science
Justin N. Maki	Jet Propulsion Laboratory	Color processing, surface/atmosphere science
Michelle E. Minitti	Arizona State University	Igneous rocks, fluorescence, rock coatings, meteorites
Timothy S. Olson	Salish Kootenai College, Montana	Material physical properties, frost
Timothy J. Parker	Jet Propulsion Laboratory	Landing site geology, stereo imaging
Scott K. Rowland	University of Hawaii, Manoa	Igneous rocks and landforms
Juergen Schieber	Indiana University, Bloomington	Sediments and sedimentary rocks

Table 8, continued.		
Name	Affiliation	Research Role
Robert J. Sullivan	Cornell University	Regolith physical properties, eolian features
Dawn Y. Sumner	University of California, Davis	Sediments and sedimentary rocks
Peter C. Thomas	Cornell University	Geodesy, photogrammetry, geology
R. Aileen Yingst	Univ. of Wisconsin, Green Bay	Regolith fines, rock properties

4.5.3 Instrument

The MAHLI instrument consists of three major parts: a camera head, a Digital Electronics Assembly (DEA) and a calibration target. The DEA and camera head are connected by a JPL-provided cable. The DEA is housed within the rover Warm Electronics Box (WEB). The camera head is mounted with other tools on the turret at the end of the rover's robotic arm. The calibration target is mounted on the robotic arm azimuth actuator housing.

4.5.3.1 Camera Head

The MAHLI camera head (Figure 24) consists of three functional elements: an optomechanical assembly, a focal plane assembly, and the camera head electronics assembly. The latter two are common to the MSL MAHLI, MARDI, and Mastcam.

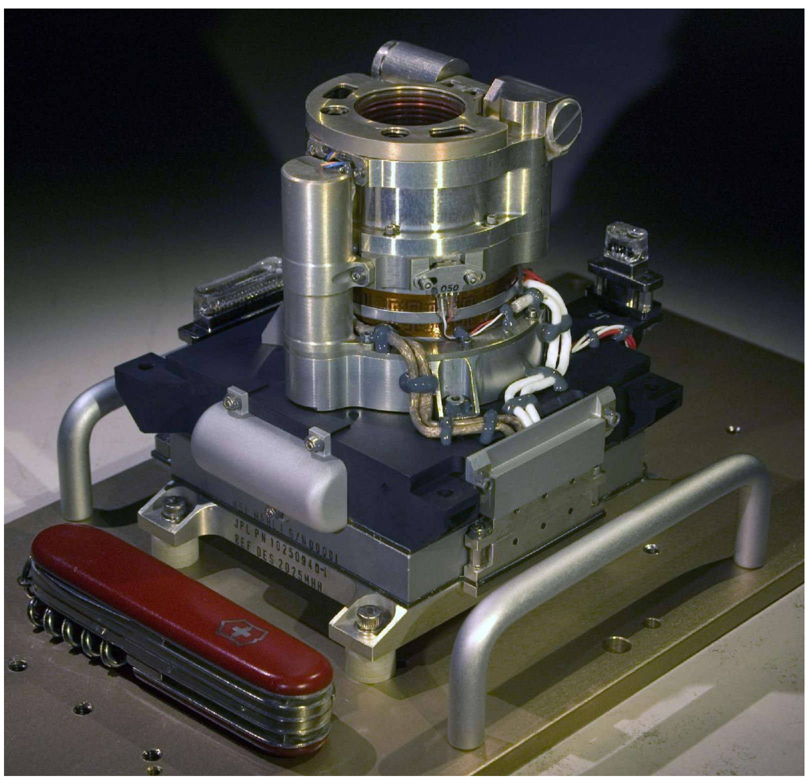

Figure 24. The flight MAHLI camera head. The pocket knife(for scale) is 88.9 mm long.

Optomechanical Assembly. The optomechanical assembly includes the integrated optics, focus and dust cover mechanisms, and a single drive motor to adjust focus and open/close the dust cover.

Optics. The designed effective focal length of the optics ranges from 18.3 mm at the closest working distance to 21.3 mm for focus at infinity. Over that same range, the focal ratio and field of view ranges from f/9.8 and 34° to f/8.5 and 39.4°. The optical design consists of a group of six fixed elements, a movable group of three elements, and the front element, a fixed sapphire window (Figure 25). Undesired near-infrared radiation is blocked by a coating deposited on the inside surface of the sapphire window. The combination of glass element transmission properties, infrared cutoff filter, and the RGB microfilters result in a spectral range for MAHLI images of 380–680 nm (Figure 26). The depth of field varies as a function of working distance, with the highest resolution MAHLI views having a depth of field of about 1.6 mm; at the pixel scale of MER MI images (~30 μm/pixel), the depth of field is about 2 mm.

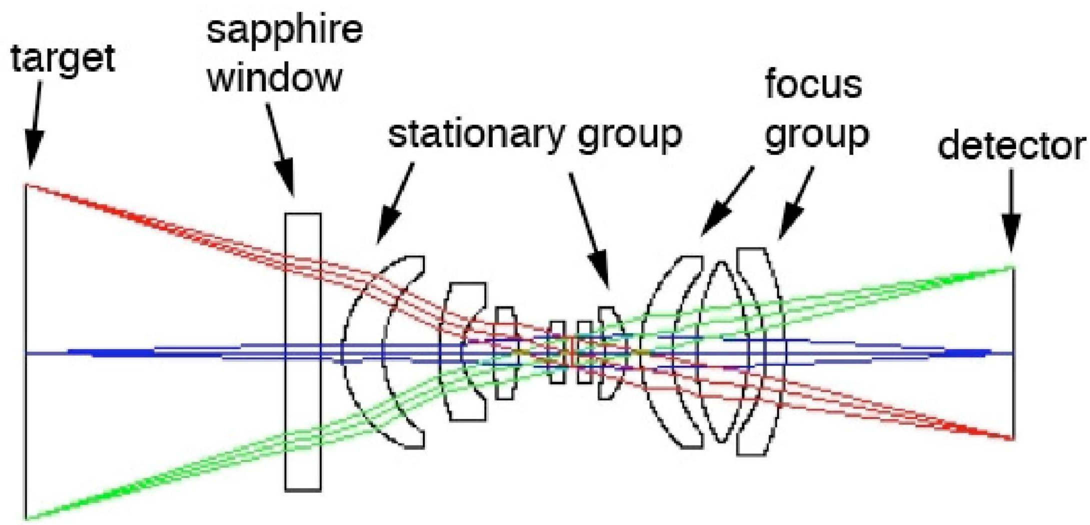

Figure 25. MAHLI optics diagram with focus group in close-focus position.

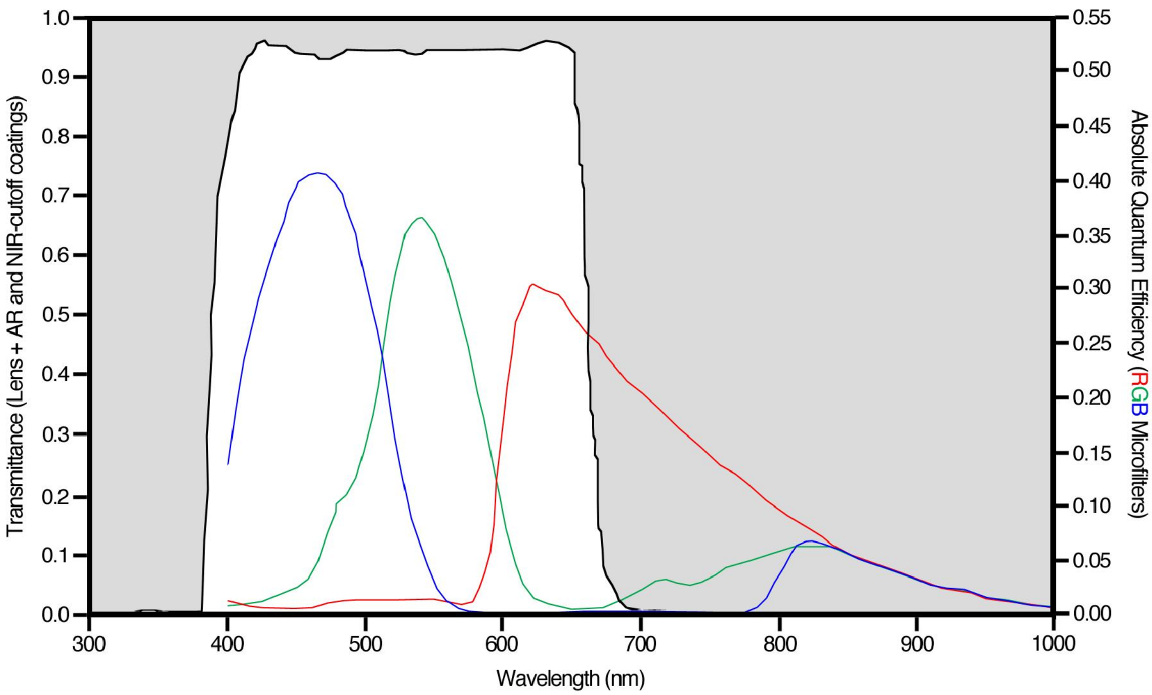

Figure 26. MAHLI spectral passband 380–680 nm. The shaded regions are not visible to MAHLI. The colored curves represent the red, green, and blue microfilters of the Kodak KAI-2020CM detector; the black curve represents the transmission properties of the lens elements and infrared cutoff coating.

Mechanical. The optics and all moving parts are sealed within the assembly to prevent dust contamination. The system is driven by a MER flight heritage Aeroflex 10 mm stepper motor with a 256:1 gearhead. The motor and gearing govern the distance the lens focus group travels. Wet lubrication (grease) of the movable parts in the motor and optomechanical assembly requires operation temperatures above –70 °C (preferably above –50 °C). Rover power constraints permitting, heaters can be applied to raise the camera head temperature to within operating range for night and early morning operations (this may also be dependent, however, on power to bring the robotic arm up to safe operating temperatures).

Dust Cover. The Aeroflex actuator also controls the commandable opening and closing of a dust cover designed to protect the front optical element and LEDs from dust contamination when the instrument is not in use. The cover has a window composed of clear, transparent Lexan®, so that, if the cover fails to open, images can still be acquired (although with the risk that adhering dust will obscure the view) and the LEDs can still illuminate targets.

Focal Plane Assembly. The Focal Plane Assembly (FPA) includes the CCD and associated electronics to amplify and digitize its output. The optics image onto a Kodak KAI-2020CM interline transfer CCD. The detector array has 1600 by 1200 active 7.4 µm square pixels. The FPA also includes the circuit elements that are tightly coupled to the CCD (e.g., the initial stage of amplification).

Camera Head Electronics. The camera head electronics includes the CCD driver electronics, the motor driver electronics, and the electronics to accept commands from and transmit data to the DEA and to power the LEDs. The camera head outputs uncompressed 12-bit pixel values at rates up to 120 Mbps over a six pair parallel interface, corresponding to a frame rate of 5 Hz. The four MAHLI white light LEDs are Avago Technologies HSMW-10x White Surface Mount LED Indicator SMT PLCC-2 (specification sheet AV02-0490EN). The two UV LEDs are Nichia Model NSHU550B.

4.5.3.2 Digital Electronics Assembly

The MAHLI Digital Electronics Assembly (DEA) is mounted within the rover Warm Electronics Box (WEB). The DEA incorporates all of the circuit elements required for data processing, compression and buffering. It also includes all power conversion and regulation for both the DEA data processing electronics and the camera head. The DEA accepts images made up of 12-bit pixel values from the camera head, converts them to 8-bit images, does commanded image compression, and buffers them in DEA nonvolatile memory. High speed pixel processing, including Bayer pattern filter interpolation and image compression, are performed in hardware in a field programmable gate array (FPGA). The MAHLI z-stacking (focus merging) is done in software.

4.5.3.3 Contact Sensor

The MAHLI contact sensor was designed and is being fabricated by JPL. It mounts around the outside of the MAHLI camera head housing. Its design is based on the contact sensor used in flight for the two MER Microscopic Imagers (MI). For the MI, the contact sensor consisted of a single “poker” that, when it made contact with the target surface, would communicate to the robotic arm to stop moving toward the target and back off the target a little bit. The MAHLI contact sensor has 2 such “poker” devices. This design works best for solid targets, such as rock, but cannot be used to poke and make contact with unconsolidated regolith fines. Work-arounds for obtaining images of fine regolith include imaging areas previously contacted by the APXS contact sensor or making no contact and using extreme caution when approaching such targets (i.e., stand-off distances with sufficient margin to prevent collision with the material).

4.5.3.4 Preflight Characterization and Calibration

The flight MAHLI instrument underwent characterization and calibration testing prior to delivery in 2008. Tests included characterization of absolute and relative radiometry (required accuracy: 10% absolute, 5% relative), light transfer and noise (e.g., dark current), geometry (focal length, field of view, distortion), resolution (modulation transfer function, point spread function), scattered and stray light, system spectral throughput, and accuracy and precision of the z-stacking range map. Additional tests will be conducted in late 2010 or early 2011 after the camera is mounted on the rover, to determine the MAHLI boresight, locate any onboard noise sources, and characterize the robotic arm’s MAHLI positioning capabilities and verify contact sensor performance.

4.5.3.5 Calibration on Mars

MSL carries the MAHLI Flight Calibration Target for color/white balance, resolution and focus checks, and verification of UV LED functionality. The target will be mounted in a vertical position (i.e., vertical when the rover is on a surface with a slope of 0°) to help prevent dust accumulation.

4.5.4 Operation

4.5.4.1 Exposures Times

Typical daylight exposure times for each MAHLI image are of the order of 5–15 milliseconds. The longer exposure value is based on the blue filter case for a low signal, solar illuminated target with a signal to noise ratio (SNR) of > 50, a target albedo of 0.1, and an incidence angle of 75°. The shorter exposure time is based on a green filter case with a high signal, solar illuminated target with signal below saturation, an albedo of 0.6, and an incidence angle of 0°. For imaging in shadow or using the white light LEDs, the bounding, dark-case exposure time is 80 milliseconds for a SNR of > 50, albedo 0.1, and solar incidence angle of 75° or higher. Imaging of UV LED-illuminated targets occurs at night and requires exposure times of the order of 2 seconds.

4.5.4.2 Image Data Formats and Onboard Image Compression

The MAHLI is capable of producing images of three formats: raw (no RGB interpolation, no compression), lossless predictive compression (no RGB interpolation, approximately 1.7:1 compression), and JPEG (with interpolated color). The amount of JPEG compression can be changed from essentially lossless to very lossy. Operationally, most images will be returned as JPEGs because of their lower data volume. The compression factor is commanded from the ground and implemented as the image is acquired. The Bayer demosaicing algorithm is based on the method of Malvar et al. (2004). In addition to the above formats, MAHLI video products are Bayer pattern-interpolated, 8-bit companded, lossy JPEG-compressed standard JPEG-formatted images concatenated into 16-frame motion-JPEG groups of pictures (GOP), with a single instrument and spacecraft header for each GOP. The instrument also returns color JPEG "thumbnail" images, typically of about 150 × 200 pixels in size. A "thumbnail" for every MAHLI image acquired is intended to be returned to Earth and these will be used to judge whether to return (and the best compression to use) images that are not required for immediate, tactical operations planning purposes.

4.5.4.3 Onboard Focus Stacking

MAHLI's onboard focus stacking (z-stacking) capability is a form of image compression. MAHLI can acquire up to 8 images on either side of best focus and then merge them to form a single best focus image and a range map. This reduces the number of images returned to Earth from 8 to 2, and the second one, the range map, is a smaller data volume, grayscale image.

The data for z-stacking are acquired in raw form. The data are RGB interpolated, and then the focus stacking algorithm uses the interpolated data as input. The software registers these focal plane images using multiresolution Kanade-Lucas-Tomasi (KLT) feature tracking with

Harris corner detection to identify feature points and track them between image pairs in the stack. The focus merge and range map are generated via a windowed Sum-Modified-Laplacian focus measure to determine the areas of best focus and uses a Gaussian interpolation for computing the depth map. The software also has an option to combine the images using multiresolution spline based image blending.

Onboard focus stacking will not always be used. It will typically be used for only the highest resolution images and MAHLI users will routinely determine under which circumstances it is to be employed, carefully considering trades between downlink availability, pixel scale, knowledge of camera head vibrational environment (during image acquisition) at the end of the robotic arm under Martian environmental conditions, and the science objectives at a given imaging target. Note that the image in Figure 23 is not a z-stacked product, it is a single-frame image.

4.5.4.4 Robotic Arm Placement of the Camera Head

The camera head is mounted to a vibration damping system on the side of the drill on the turret at the end of MSL's robotic arm. The JPL-provided contact sensor, described above, is used to prevent the camera head from impacting a target rock. Arm placement is a function of two factors: the ability of the robotic arm to place the camera head in the desired location, and the accuracy of the navigation and hazard camera images and visualization tools, coupled with the commanding tools, to allow users to generate the commands that will place the camera in the desired position. The robotic arm will have better placement capabilities for targets that are repeatedly imaged (e.g., the MAHLI Flight Calibration Target, a rock that is returned to more than once) or that has been contact-sensed by the APXS contact sensor, first. Placement of the MAHLI camera head for the first time, however, may have an uncertainty of as much as ~20 mm in three dimensions.

4.5.4.5 Operations Team

The MAHLI will be operated at Malin Space Science Systems (MSSS, San Diego, California) by a team of dedicated spacecraft instrument operations professionals that have been operating cameras on multiple Mars spacecraft since 1997. They are responsible, based on science team input, for commanding the instrument and providing the information needed to command placement of the robotic arm for MAHLI imaging. They are also responsible for receipt and logging of the MAHLI science and engineering data, reporting on and maintaining instrument health, and archiving of the MAHLI data with the NASA PDS.

4.5.4.6 Data Archiving

Most MAHLI data will be returned to Earth as color JPEGs ready for viewing with standard JPEG-viewing software (including web browsers and many e-mail tools). Pre-validated "raw" MAHLI science data are required by NASA to be made available to the entire world via the internet within 24 hours of receipt on Earth. MAHLI image data will be validated and archived with the NASA PDS following a schedule determined by the MSL Project. PDS data products will be archived in the form received from Mars (i.e., raw) and (resources permitting) in geometrically and radiometrically calibrated forms in a standard PDS file format. Products generated by the science or operations teams for data analysis or tactical planning purposes (e.g., mosaics, stereopair products) might be archived with the PDS or (more likely) made available through scientific publications, depending upon resource availability.

4.5.4.7 Examples of How MAHLI Will Be Used

MAHLI has a range of capabilities and presents considerable flexibility for use. Some ways the camera will be used include (but are not limited to):

- Closeup imaging of rocks and fine regolith targets from a near-normal (i.e., along z-axis of the camera lens) viewing position.
- Context imaging of targets viewed at highest MAHLI resolutions.
- Imaging oblique views (e.g., bug's eye, dog's eye, or standing-human's eye views) of rocks, regolith, and terrain.
- Night imaging.
- Searching for fluorescent materials using the UV LEDs.
- Observing seasonal frost; monitoring changes in frost over night.
- Mosaicing and stereo-pair imaging.
- Imaging of terrain and dust-raising event monitoring when MAHLI is in a stowed position (when robotic arm/turret are stowed).
- Imaging of the MAHLI Flight Calibration Target.
- Sky imaging (requires knowledge of position of Sun in the sky) for flat field calibration.
- Drill hole imaging (might involve shining LED illumination into the hole).
- Sample Observation Tray imaging of a split of drill or CHIMRA samples.
- Periscope Imaging—robotic arm is extended upward to allow MAHLI to look over the top of something that the other cameras cannot reach (the robotic arm can place MAHLI higher above the ground than the top of the Remote Sensing Mast).
- Acquiring scientific video sequences (e.g., documenting grain movement on the surface).
- Acquiring public outreach or documentary video sequences (e.g., opening of a sample inlet cover; viewing landscape go by as rover drives and MAHLI is stowed; moving rover a very short distance while arm is deployed such that MAHLI can observe wheels rolling over the surface; movement of Remote Sensing Mast).
- Rover problem diagnosis (view under the rover as done with on Spirit, only this time in focus and in color; view wheels from the side; look down inside CheMin or SAM sample inlets).
- Rover self portraits (for education/public outreach) by holding camera head up above the rover or out at some distance from the rover.

4.6 MARDI (Mars Descent Imager)

The Mars Descent Imager (MARDI) is a fixed-focus color camera fixed-body-mounted to the fore-port-side of the MSL rover, even with the bottom of the rover chassis. The optical axis points in the +Z direction (toward the ground in the rover coordinate system) (Figure 27). The camera will take 1600 × 1200 pixel images at ~5 frames per second throughout the period of time between heatshield separation and touchdown plus a few seconds (a period of about two minutes). The rover software issues a “start imaging” command and the camera operates autonomously until the rover software determines that landing has succeeded and issues a “stop imaging” command. The data are written into permanent flash memory in realtime during acquisition for later transmission.

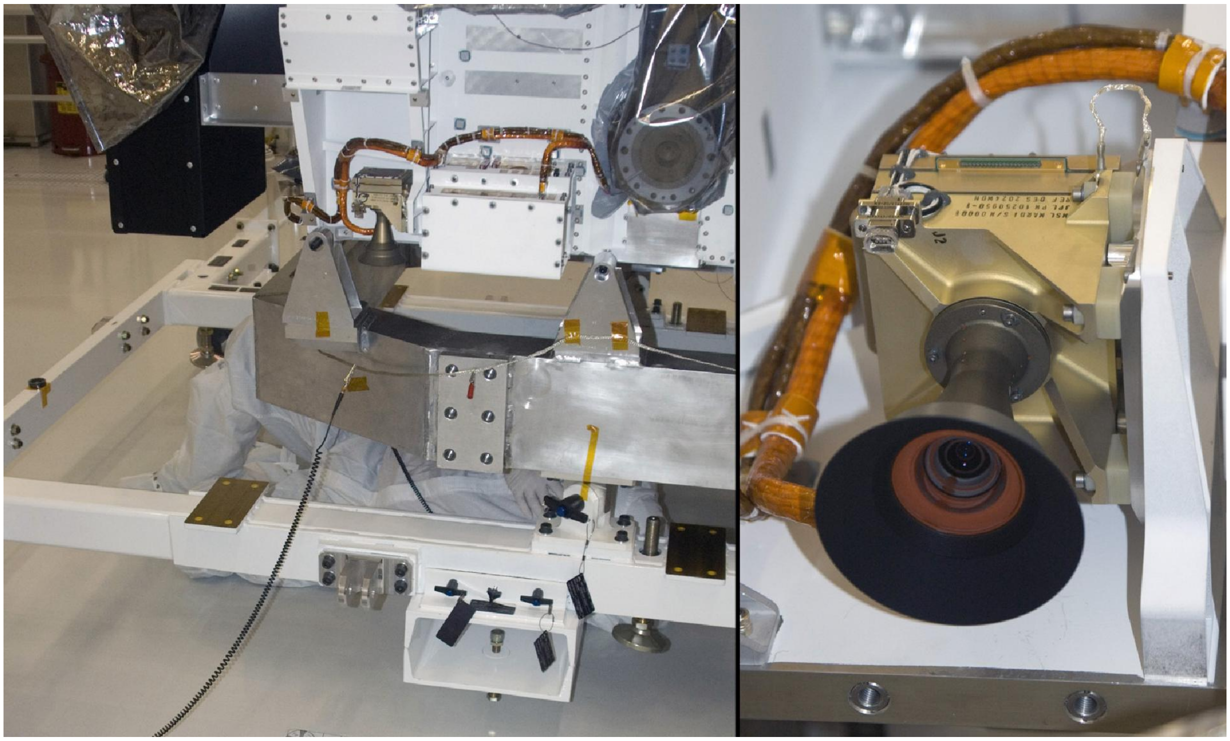

Figure 27. MARDI as installed on MSL flight rover (September 2008).

The rectangular field of view (FOV) of the detector is inscribed within the 90° diameter circular FOV of the lens, yielding a 70° × 55° frame with the long axis transverse to the direction of motion. The IFOV of the camera is ~0.76 milliradians, which provides in-focus pixel scales that range from 1.5 m at 2 km altitude to 1.5 mm at 2 m altitude, and cover between 2.4 × 1.8 km and 2.4 × 1.8 m at these respective altitudes. At distances less than 2 m, out-of-focus blurring increases at the same rate that spatial scale decreases, resulting in a constant spatial sampling of 1.5 mm. Many hundreds of images will be acquired at ground sampling distances many times greater than available from orbit.

An 8 gigabyte internal buffer permits the camera to acquire over 4,000 raw frames (equivalent to 800 seconds of descent, which is many times the actual descent duration). Integrated over the detector is a RGB Bayer pattern filter (GR/BG unit cell). For a landing at 3 PM LMST (solar incidence angle of 55°) and a surface albedo of 0.2, the nominal SNR will be ~80:1 in the green and red, and > 50:1 in the blue. The camera is capable of losslessly compressing the images, or applying lossy JPEG compression, in realtime during acquisition and storage, although the intent is to take the images in raw format and apply compression just prior to downlink to Earth. Thumbnail images of 200 × 150 pixels can be created simultaneously with the processing and storage of the realtime images, but will likely be generated again just prior to downlink. Large angular rate motion while the vehicle is descending on parachute, and rocket thruster induced vibratory motion while the vehicle is descending on its landing engines, are likely to blur many of the images despite a 1.3 millisecond exposure time.

MARDI's primary objectives are to determine where exactly the vehicle has landed and to provide a geologic and engineering-geologic framework of the landing site for early operations. The rover is expected to leave the area imaged by MARDI after the first few weeks of the mission. It is likely that only a subset of the images will have been transmitted by this time (e.g., thumbnails plus a sampling of full-frame images). Vehicle horizontal offset between images within the descent sequence may permit digital elevation models (DEMs) to be created from the descent images. Additional objectives of the investigation are to examine vehicle ground-referenced motion deviations from inertial measurement unit (IMU) derived inertial position during descent to extract lower boundary layer wind velocity, and to help develop and test algorithms for future autonomous landing and hazard avoidance systems.

Although MARDI was descoped from the MSL payload in the summer of 2007, NASA permitted Malin Space Science Systems (MSSS) to use its own resources to complete the instrument. Subsequently NASA reinstated the instrument for flight. MSSS will process the data and archive them within the PDS.

4.7 Mastcam (Mast Camera)

The Mast Camera is a two-instrument suite of imaging systems mounted on the MSL rover's Remote Sensing Mast (RSM), with the boresight ~1.97 m above the bottom of the wheels when the rover is on a flat surface. As proposed and as late as the instrument Critical Design Review (CDR) in February 2007, the Mastcam consisted of two identical area-array digital cameras each with a 6.5-100 mm (15:1) variable-focal length (VFL) (zoom telephoto) lens, whose electronics were identical to the electronics of the MARDI and MAHLI cameras, also provided by Malin Space Science Systems. These cameras would have provided same focal length binocular vision for stereoscopic studies at all focal lengths as well as 14 filter positions for scientific multispectral studies. In September 2007, NASA directed that the zoom capability be removed from the cameras. Between November 2007 and January 2008, new, fixed-focal length (FFL) Mastcam designs were generated, based on using the MAHLI focus mechanism design; these cameras are described below. In early 2010, NASA reconsidered the VFL cameras and work resumed on assembling these cameras, which will replace the FFL cameras described here if the work is completed in time and the instruments meet their requirements.

The FFL Mastcams (we use the plural here because the "eyes" of the FFL Mastcam investigation are not identical) as built and delivered consist of two cameras with different focal lengths and different science color filters (Figure 28). The stereo baseline of the pair is ~24.5 cm. One camera, referred to as the Mastcam-34 (M-34), has a ~34 mm focal length, f/8 lens that illuminates a 15° square field-of-view (FOV), 1200 × 1200 pixels on the 1600 × 1200 pixel detector. The other camera, the Mastcam-100 (M-100), has a ~100 mm focal length, f/10 lens that illuminates a 5.1° square, 1200 × 1200 pixel FOV. Both cameras can focus between 2.1 m (nearest view to the surface) and infinity. The M-100 IFOV is 7.4×10^{-5} radians, yielding 7.4 cm/pixel scale at 1 km distance and ~150 µm/pixel scale at 2 m distance. The M-34 IFOV is 2.2×10^{-4} radians, which yields a pixel scale of 450 µm at 2 m distance and 22 cm at 1 km. A strict

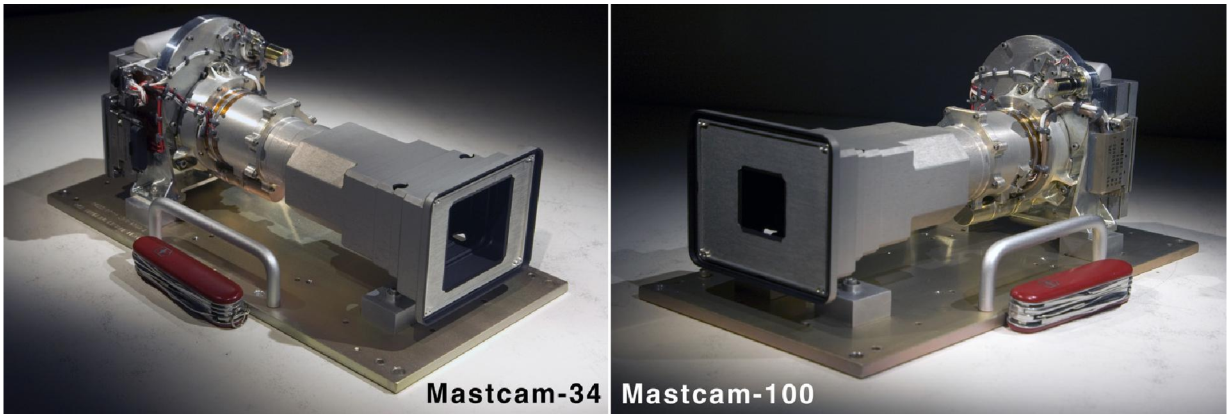

Figure 28. Fixed-focal length (FFL) Mastcams. The only distinguishing difference in outward appearance between the cameras is the aperture size in the front baffle.

definition of “in focus” is used for these cameras wherein the optical blur circle is equal to or less than one pixel across.

Each camera has an 8 gigabyte internal buffer that permits it to store over 5,500 raw frames. Each camera is capable of losslessly compressing the images, or applying lossy JPEG compression, in realtime during acquisition and storage, although it is more likely that images will be acquired raw and compressed just prior to downlink to Earth. The 8 gigabytes is equivalent to a full-scale mosaic of 360° × 80° imaged in 3 science color filters with ≥ 20% overlap between adjacent images. With minimally lossy JPEG compression (e.g., a factor of 2), a mosaic including <u>all</u> science filters could be acquired. This is much more than can be transmitted back to Earth under normal communication limitations. Subframing of images is only available at acquisition, not during later processing. Color thumbnail images of 150 × 150 pixels can be created simultaneously with the acquisition of full scale images, or during processing just prior to downlink.

Both FFL Mastcams are color imagers. Integrated over each detector is an RGB Bayer pattern filter (GR/BG unit cell). A broadband (IR cutoff) filter through which RGB imaging will occur is included in one of the 8 filter positions within each camera's filter wheel. Both cameras also include a narrow band filter with 10^5 neutral density attenuation to image the Sun for atmospheric studies. The filters are distributed between the M-34 and M-100 to ensure each camera can address some of the compositional objectives of the investigation should the other camera fail (Table 9). The science filters are imaged through the RGB filter array (see Figure 29). For some science filters, the throughput in some pixels of the unit cell will be poorer than in other pixels, but beyond 700 nm, all three Bayer colors have nearly identical throughput (i.e., they have large IR leaks, which we are using to our advantage). Figure 30 shows examples taken with the Flight FFL M-100 and its Bayer filter array through the IR-cutoff filter and through a 1035 ± 50 nm IR science filter. In-flight calibration uses the MER Pancam spare calibration target with magnets mounted beneath the four color chips and "white" and gray surfaces to provide dust-free spots (following the approach of the Phoenix SSI team).

Table 9. Mastcam color filter passbands

Wavelength range (nm)	34 mm Medium Angle Camera	100 mm Narrow Angle Camera
440 ± 12.5	X	X
440 ± 10 + ND^5	X	
525 ± 10	X	X
550 ± 130	X	X
675 ± 10	X	
750 ± 10	X	
800 ± 10		X
865 ± 10	X	
880 ± 10 + ND^5		X
905 ± 12.5		X
935 ± 12.5		X
1035 ± 50	X	X
Pink color indicates filters common to both cameras		

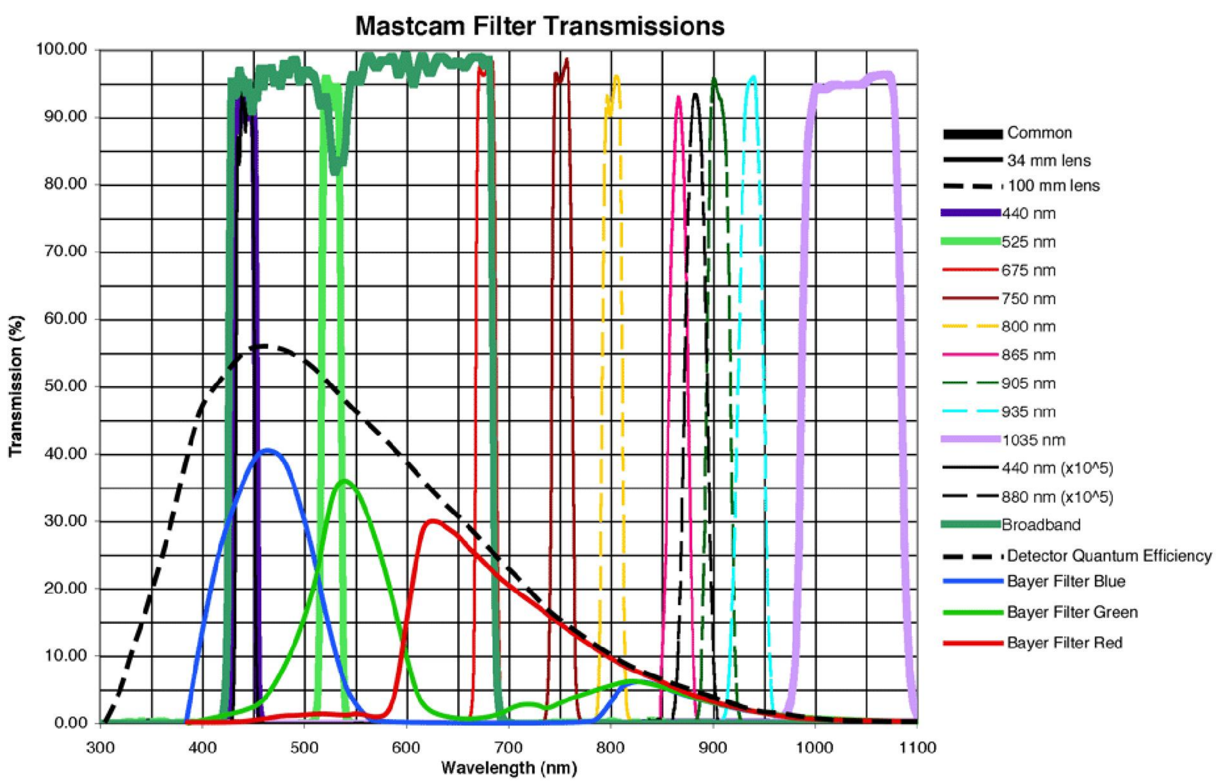

Figure 29. Relative passbands of the science color filters, RGB color filter array, and quantum efficiency of CCD detector. The latter two are not shown to scale.

Figure 30. Two Mastcam-100 images, both taken with the Bayer color filters. Left image shows the single image RGB capability. Right image shows the uniform spectral response in the IR as viewed by the Bayer filters.

Mastcam hardware and internal processing permit a wide range of operational flexibility. Each camera is capable of acquiring images at very high frame rates compared to previous missions, including 720p high definition video (1280 × 720 pixels) at ~10 frames per second, and full science frames at somewhat greater than 5 fps. The full range of focus requires between 45 and 60 seconds, but autofocus around a predicted focus point can be accomplished much faster. Changes to consecutive filter positions take 5-8 seconds. It takes between 30 and 45 seconds to rotate the filter wheel a full 360°. Mosaic acquisition is paced by the time it takes the RSM to move and for motion-induced vibration to settle (<< 5 seconds between movements). The cameras include auto- and commanded-focus capability and auto- and commanded-exposure control. Radiometric accuracy is ≤ 10-15%, and precision 5-8%. Exposure times are expected to vary from a few tens of msec to a couple of hundred msec, depending on the band-pass filter and the desired signal-to-noise ratio.

The primary objectives of the Mastcam investigation are to characterize and determine details of the history and processes recorded in geologic material at the MSL landing site. Both Mastcams can acquire panoramic, color, multispectral images and together are able to acquire stereoscopic observations to address the following specific objectives: (a) observe landscape physiography and processes in order to provide a full description of the topography, geomorphology, and geologic setting of the MSL landing site and the nature of past and present geologic processes at the site; (b) examine the properties of rocks (i.e., outcrops down to clasts as small as 0.15 mm) and the results of interaction of rover hardware with rocks to help determine morphology, texture, structure, mineralogy, stratigraphy, rock type, history/sequence, and depositional, diagenetic, and weathering processes for these materials; (c) study the properties of disaggregated materials (fines as small as 0.15 mm) to determine the processes that acted on these materials and individual grains within them, including physical and mechanical properties, the results of interaction of rover hardware with fines, plus stratigraphy, texture, mineralogy, and depositional processes; (d) view frost, ice, and related processes, if present, to determine texture, morphology, thickness, stratigraphic position, and relation to regolith and, if possible, observe changes over time; also examine ice-related (*e.g*., periglacial) geomorphic features; (e) document atmospheric and meteorological events and processes by observing clouds, dust-raising events, properties of suspended aerosols (dust, ice crystals), and (using the video capability) eolian transport of fines; (f) support/facilitate rover operations, analytical laboratory sampling, contact instrument science, and other MSL science by assisting rover navigation, acquiring images that help determine the location of the Sun, horizon features, and provide information pertinent to rover trafficability (*e.g*., hazards at hundreds of meters distance), and for other MSL science instruments, provide data that helps the MSL science team identify and characterize materials to be collected or studied *in situ*.

4.8 RAD (Radiation Assessment Detector)

The Radiation Assessment Detector (RAD) is an energetic particle analyzer designed to characterize the full spectrum of energetic particle radiation at the surface of Mars, including galactic cosmic rays (GCRs), solar energetic particles (SEPs), secondary neutrons and other particles created both in the atmosphere and in the Martian regolith.

The RAD instrument (Figure 31) consists of a charged particle telescope comprised of three solid-state detectors and a cesium iodide (CsI) calorimeter. An additional BC-432 scintillating plastic channel is used together with the CsI calorimeter and an anti-anticoincidence shield to detect and characterize neutral particles (i.e., neutrons and gamma rays). The outputs of the various photodiodes, used with the CsI and scintillating plastic, and solid-state detectors are converted to digital pulse height discriminated signals for further processing. The digital logic includes an embedded microcontroller to bin and format the data. The RAD particle and energy coverage is shown in Figure 32. The RAD instrument is mounted just below the top deck of the rover with the charged particle telescope pointed in the zenith direction (Figure 31).

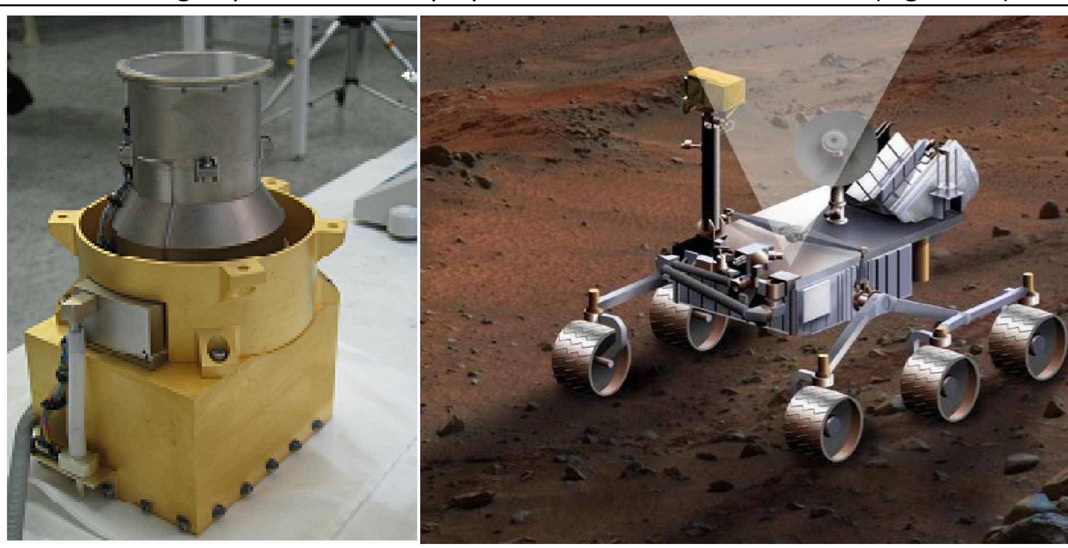

Figure 31. Photo of RAD flight model in the lab (left), and artwork of an older MSL rover design, showing RAD charged particle channel 65⁰ field-of-view pointing toward the zenith (right).

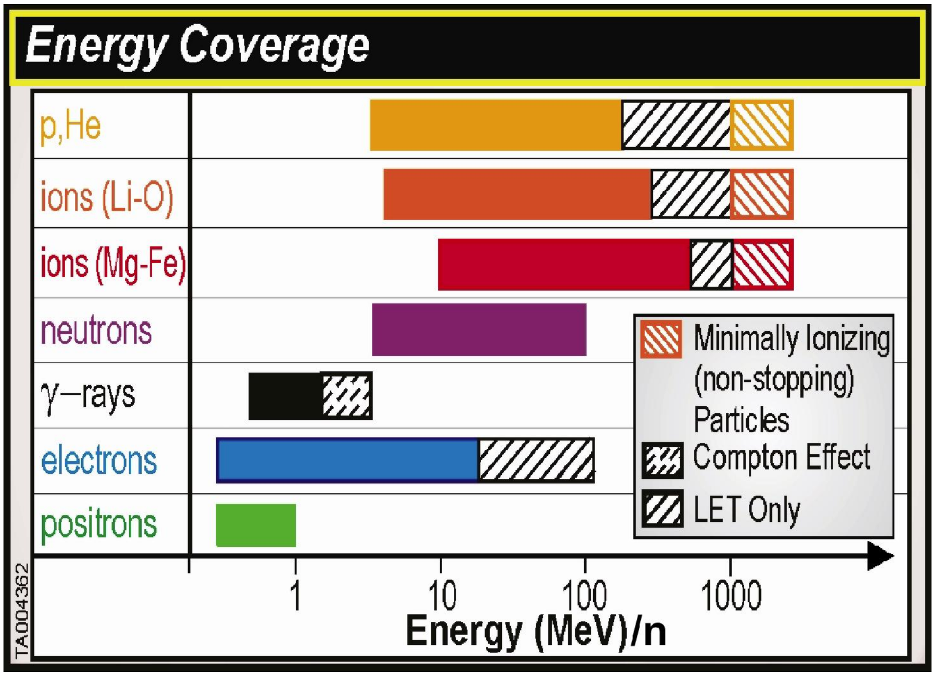

Figure 32. RAD energy coverage for both charged and neutral particles.

The RAD instrument will be used throughout the mission, including part of the cruise phase, to characterize the radiation environment of MSL. It is desirable for the instrument to be powered continuously while on the Martian surface. However, because of rover energy constraints, the present plan is to acquire roughly 15-minute observations every hour throughout each sol.

RAD's primary science objectives are to:

- Characterize the energetic particle spectrum at the surface of Mars,
- Determine the radiation dose rate for humans on the surface of Mars,
- Enable validation of Mars atmospheric transmission models and radiation transport codes,
- Provide input to the determination of the radiation hazard and mutagenic influences to life, past and present, at and beneath the Martian surface, and
- Provide input to the determination of the chemical and isotopic effects of energetic particles on the Martian surface and atmosphere.

The RAD science team members are listed in Table 10.

Table 10. RAD science team PI and Co-Is

Name	Institution
Don Hassler, PI	SwRI
Stephan Böttcher	Univ. Kiel (CAU), Germany
David Brinza	Jet Propulsion Laboratory
Mark Bullock	SwRI
Sonke Burmeister	Univ. Kiel (CAU), Germany
Timothy Cleghorn	NASA JSC
Frank Cucinotta	NASA JSC
David Grinspoon	Denver Museum of Nature & Science
César Martín	Univ. Kiel (CAU), Germany
Reinhold Mueller-Mellin	Univ. Kiel (CAU), Germany
Arik Posner	NASA Headquarters
Scot Rafkin	SwRI
Gunther Reitz	DLR, Germany
Robert Wimmer-Schweingruber	Univ. Kiel (CAU), Germany
Cary Zeitlin	SwRI

4.9 REMS (Rover Environmental Monitoring Station)

REMS has been designed to record six atmospheric parameters: wind speed/direction, pressure, relative humidity, air temperature, ground temperature, and ultraviolet radiation. All sensors are located around three elements: two booms attached to the rover Remote Sensing Mast (RSM), the Ultraviolet Sensor (UVS) assembly located on the rover top deck, and the Instrument Control Unit (ICU) inside the rover body.

The booms are approximately 1.5 m above ground level. Boom length is similar to the RSM diameter, and therefore the wind flow perturbation by the RSM may reach the boom tip where the wind sensor is located. The two booms are separated in azimuth by 120° to help insure that at least one of them will record clean wind data for any given wind direction. Figure 33 shows the booms' relative position. There is a 50 mm height difference to minimize mutual wind perturbation.

Boom 2, which points in the driving direction of the rover, has wind sensors and the relative humidity sensor. Boom 1, which looks to the side and slightly to the rear of the rover, hosts another set of wind sensors and the ground temperature sensor. Both booms have an air temperature sensor.

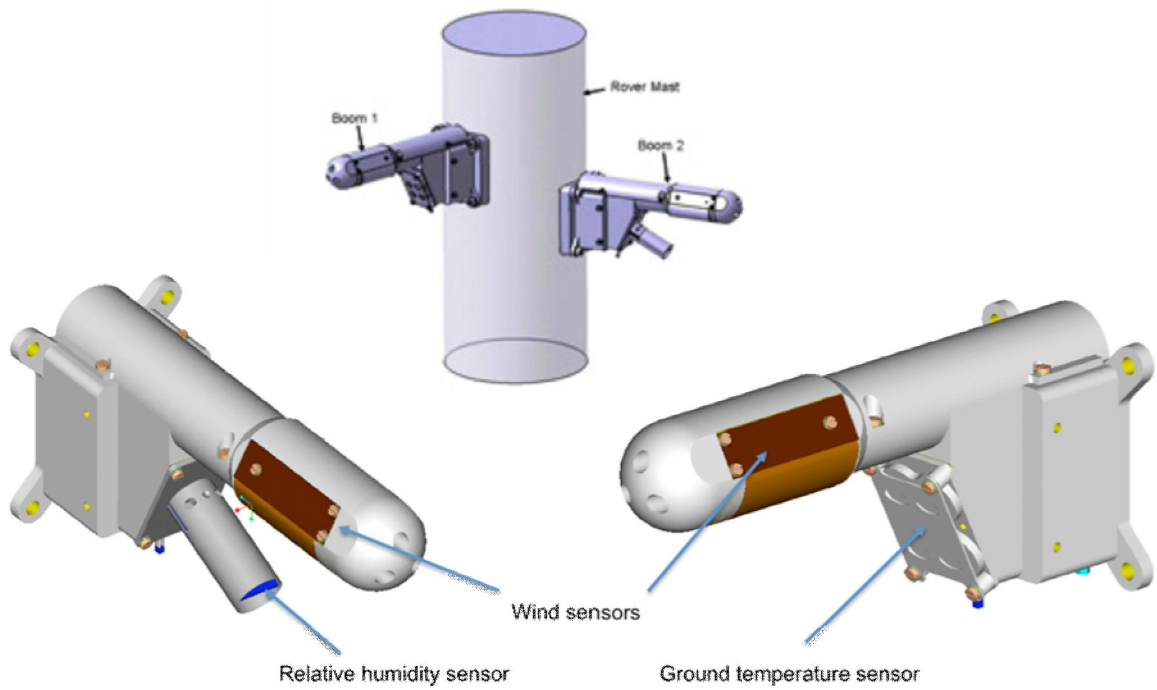

Figure 33. This figure shows a sketch of the boom locations on a section of the rover mast, and the booms themselves. On the right is Boom 1 with wind and ground temperature sensor and on the left is Boom2 with wind and humidity sensors. On both booms the conditioning electronics are located on the back, close to the attachment point.

Wind speed and direction will be derived based on information provided by three two-dimensional wind sensors on each of the booms. The three sensors are located 120° apart around the boom axis. Each of them will record local speed and direction in the plane of the sensor. The convolution of the 12 data points will be enough to determine wind speed as well as pitch and yaw angle of each boom relative to the flow direction. The requirement is to determine horizontal wind speed with 1 m/sec accuracy in the range of 0 to 70 m/sec, with a resolution of 0.5 m/sec. The directional accuracy is expected to be better than 30 deg. For vertical wind the range is 0 to 10 m/sec, and the accuracy and resolution are the same as for horizontal wind.

As mentioned previously, the wind field at the booms will be perturbed by the RSM and by the rover itself. Calibration will be done via a variety of wind tunnel tests under Mars conditions as well as numerical analysis. Simulations will be used to obtain results where tests conditions cannot be reproduced on Earth.

Ground temperature will be recorded with a thermopile on Boom 1 that views the Martian surface to the side of the rover (see Figure 9 and Figure 33) through a filter with a passband of 8 to 14 microns (Sebastián et al., 2010). The requirement is to measure ground brightness temperature over the range from 150 to 300 K with a resolution of 2 K and an accuracy of 10 K.

Air temperature will be recorded at both booms with a PT1000-type sensor placed on a small rod long enough to be outside the mast and boom thermal boundary layers. Its measurement range is 150 to 300 K. It has an accuracy of 5 K and a resolution of 0.1 K.

Boom 2 houses the humidity sensor, which is located inside a protective cylinder. That sensor will measure relative humidity with an accuracy of 10% in the 200-323 K range and with a resolution of 1%. A dust filter protects it from dust deposition.

Two of the main constraints on the REMS instrument design are the need for the booms to survive and operate in a broad range of temperatures, and for the entire instrument to have a mass less than 1.3 kg. Both conditions have required the development of an ASIC for data conditioning which must survive a -130 °C to +70 °C temperature range and minimize power consumption for operation.

The UV sensor will be located on the rover deck and is composed of six photodiodes in the following ranges: 315-370 nm (UVA), 280-320 nm (UVB), 220-280 nm (UVC), 200-370 nm (total dose), 230-290 nm (UVD), and 300-350 nm (UVE), with an accuracy better than 8% of the full range for each channel, computed based on Mars radiation levels and minimum dust opacity. The photodiodes face the zenith direction and have a field of view of 60°. The sensor will be placed on the rover deck without any dust protection. To mitigate dust degradation, a magnetic ring has been placed around each photodiode with the aim of maximizing their operational time. Nevertheless, to evaluate dust deposition degradation, images of the sensor will be recorded periodically. Comparison of these images with laboratory measurements will permit evaluation of the level of dust absorption.

The pressure sensor will be located inside the rover body and connected to the external atmosphere via a tube. The tube exits the rover body through a small opening with protection against dust deposition. Its measurement range goes from 1 to 1150 Pa with an end-of-life accuracy of 20 Pa (calibration tests give values around 3 Pa) and a resolution of 0.5 Pa. As this component will be in contact with the atmosphere, a HEPA filter will be placed on the tube inlet to avoid contaminating the Mars environment.

Systematic measurement is the main driver for REMS operation. Each hour, every sol, REMS will record 5 minutes of data at 1 Hz for all sensors. This strategy will be implemented based on a high degree of autonomy in REMS operations. The instrument will wake itself up each hour and after recording and storing data, will go to sleep independently of rover operations. REMS will record data whether the rover is awake or not, and both day and night. It is expected that under certain conditions, the ground temperature and humidity sensor measurements will require the integration of multiple measurement samples within the 5-minute interval in order to meet their science requirements.

REMS operation is designed assuming an integrated total of three hours of operation each day, primarily constrained by power availability. Nevertheless, the REMS science team will have the capability to define additional prescheduled observation periods with durations longer than 5 minutes and located at any time during the day. Since the hourly observations will use a total of two hours of operational time, the third hour can be scheduled as a continuous block, for example. Another option that has been implemented in REMS flight software is a simple algorithm to lengthen some of the regular observations autonomously when an atmospheric event is detected.

The REMS science team is shown in Table 11. The main science objectives that the science team will focus on are:

- Signature of the Martian general circulation and mesoscale phenomena near the surface (e.g., fronts, jets)

- Microscale weather systems (e.g., boundary layer turbulence, heat fluxes, dust devils)
- Local hydrological cycle (e.g., spatial and temporal variability, diffusive transport from regolith)
- Destructive potential of UV radiation, dust UV optical properties, photolysis rates, and oxidant production
- Subsurface habitability based on ground-atmosphere interaction

Table 11. REMS science team

Team member	Science theme and role	Institution
Javier Gómez-Elvira	Principal Investigator	Centro de Astrobiología (CSIC-INTA)
Manuel de la Torre Juárez	Investigation Scientist Boundary layer and atmosphere dynamics	Jet Propulsion Laboratory
Robert Haberle	Global atmosphere dynamics	NASA Ames Research Center
Ari-Matti Harri	Limited area atmospheric dynamics	Finnish Meteorological Institute
Miguel Ramos	Microclimate process, atmosphere-ground interaction	Universidad de Alcalá de Henares
Jesús Martínez Frías	Atmosphere-ground interaction	Centro de Astrobiología (CSIC-INTA)
Nilton Renno	Local atmospheric dynamics	University of Michigan
Mark Richardson	Mars boundary layer	Ashima Research

4.10 SAM (Sample Analysis at Mars Instrument Suite)

The Sample Analysis at Mars (SAM) Suite Investigation in the MSL Analytical Laboratory is designed to address the present and past habitability of Mars by exploring molecular and elemental chemistry relevant to life. SAM addresses carbon chemistry through a search for organic compounds, the chemical state of light elements other than carbon, and isotopic tracers of planetary change.

SAM is a suite of three instruments, a Quadrupole Mass Spectrometer (QMS), a Gas Chromatograph (GC), and a Tunable Laser Spectrometer (TLS). The QMS and the GC can operate together in a GCMS mode for separation (GC) and definitive identification (QMS) of organic compounds. The TLS obtains precise isotope ratios for C and O in carbon dioxide and measures trace levels of methane and its carbon isotope.

Three questions about the ability of Mars to support past, present, or future life are addressed by SAM's five science goals as stated in Table 12.

Table 12. SAM goals and primary habitability questions

Science and Measurement Goal	Habitability Question
1) Survey carbon compound sources and evaluate their possible mechanisms of formation and destruction 2) Search for organic compounds of biotic and prebiotic importance, including methane	What does the inventory or lack of carbon compounds near the surface of Mars tell us about its potential habitability?
3) Reveal the chemical and isotopic state of elements (i.e. N, H, O, S and others) that are important for life as we know it. 4) Determine atmospheric composition including trace species that are evidence of interactions between the atmosphere and soil.	What are the chemical and isotopic states of the lighter elements in the solids and in the atmosphere of Mars and what do they tell us about its potential habitability?
5) Better constrain models of atmospheric and climatic evolution through measurements of noble gas and light element isotopes.	Were past habitability conditions different from today's?

The three SAM instruments are supported by a sample manipulation system (SMS) and a Chemical Separation and Processing Laboratory (CSPL) that includes high conductance and micro valves, gas manifolds with heaters and temperature monitors, chemical and mechanical pumps, carrier gas reservoirs and regulators, pressure monitors, pyrolysis ovens, and chemical scrubbers and getters. The Mars atmosphere is sampled by CSPL valve and pump manipulations that introduce an appropriate amount of gas through an inlet tube to the SAM instruments. The solid phase materials are sampled by transporting finely sieved materials to one of 74 SMS sample cups that can then be inserted into a SAM oven and thermally processed for release of volatiles. The SAM mechanical configuration is illustrated in Figure 34 and a top level schematic of its sample flow configuration is shown in Figure 35.

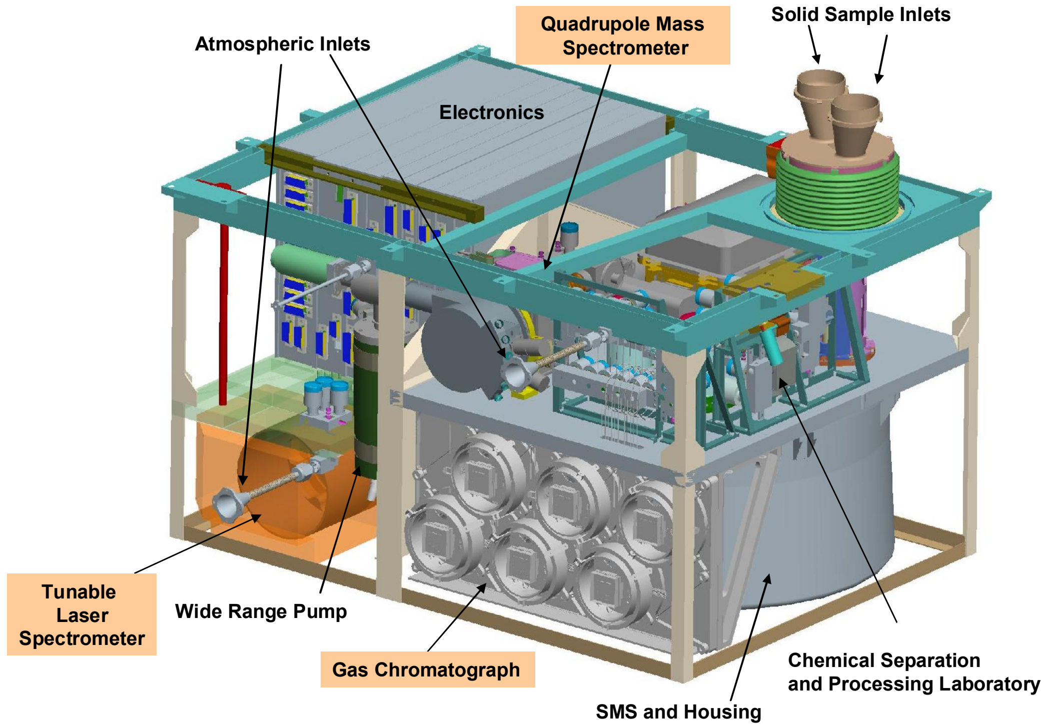

Figure 34. The illustration of the mechanical configuration of SAM shows the three instruments and several elements of the Chemical Separation and Processing Laboratory.

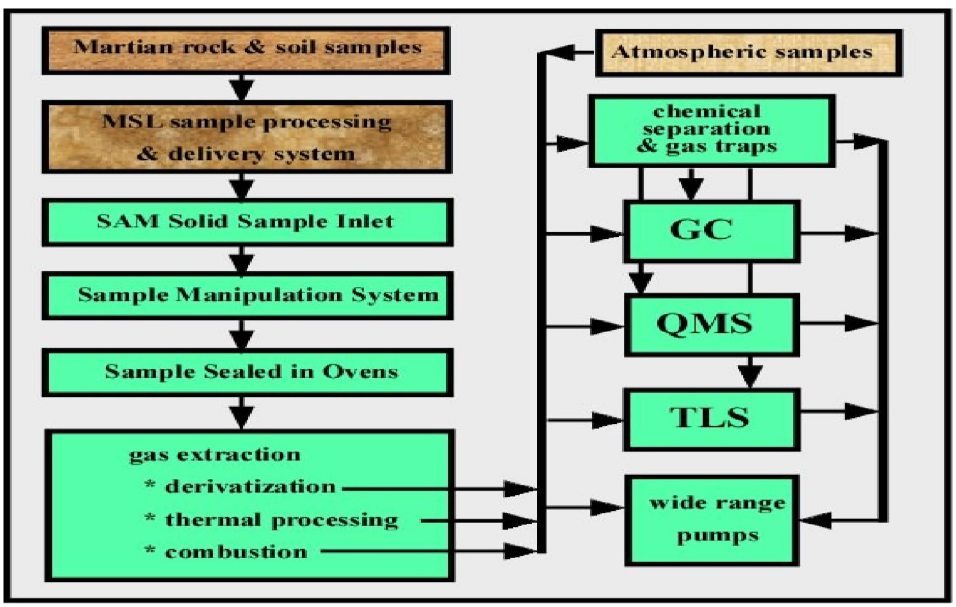

Figure 35. The path of solid and gas samples delivered by MSL subsystems to the SAM instruments is shown. Arrows designate the direction of gas and solid transport.

The SAM PI and Co-I names, institutions, and a primary science focus area for each are listed in Table 13. The SAM science team also includes collaborators not listed here.

Table 13. SAM Co-Investigators and their primary science focus

Name	Institution	Primary Science Focus
Paul Mahaffy, PI	NASA Goddard	SAM Science Team Lead
Pamela Conrad, Deputy PI	NASA Goddard	Organics/mineralogy
Sushil Atreya	Univ. Michigan	Atmospheric chemistry and surface exchange, astrobiology, climate evolution
Will Brinckerhoff	NASA Goddard	Refractory organics analysis & SAM calibration
Michel Cabane	Univ. Paris/SA	GC team institutional PI and organics analysis
Patrice Coll	Univ. Paris XII	Organics analysis and GC surface operations. Evolved gas signatures of carbonates
Fred Goesmann	Max Planck	Chromatography and organics analysis
Stephen Gorevan	Honeybee Robotics	SMS provider and sample processing
Bruce Jakosky	Univ. Colorado	Atmospheric loss and isotopic signatures
John Jones	NASA JSC	Mineralogy/petrology
Laurie Leshin	NASA Headquarters	Light isotopes and atmospheric evolution
Chris McKay	NASA Ames	Organics analysis and terrestrial analogues
Doug Ming	NASA JSC	Evolved gas analysis and mineralogy and comparisons with MER and Phoenix investigations. Surface operations.
Dick Morris	NASA JSC	Mineralogy and evolved gas analysis. Surface operations.
Rafael Navarro-González	Univ. Nacional Autónoma Mexico	Organics analysis and terrestrial analogues
Toby Owen	Univ. Hawaii	Nitrogen isotope and noble gas analysis. Atmospheric chemistry and composition. D/H in near surface water and oxygen isotopes in CO_2.
Bob Pepin	Univ of Minn.	Noble gases and atmospheric evolution
François Raulin	Univ. Paris	Isotopes in solids
François Robert	Museum Nat. Hist. Naturelle	Macromolecular fragmentation through pyrolysis and biomarker identification through odd/even carbon number patterns
Steve Squyres	Cornell Univ.	SAM/MSL operations and geochemistry
Andrew Steele	Carnegie Inst.	Evaluation of refractory carbon and production mechanisms
Chris Webster	Jet Propulsion Laboratory	TLS Institutional PI / atmospheric methane & isotope analysis. Seasonal variations of trace atmospheric species.

SAM is designed to deliver nine data set types that are acquired via the experiment sequences described in Table 14. These experiment sequences may utilize different elements of the SAM suite. In addition to these science sequences, the SAM vacuum elements will be cleaned as necessary during the course of the mission by in situ bakeout.

Key characteristics of the SAM instrument components are summarized in Table 15.

Table 14. SAM experiment sequences

Solid Sample Analysis Sequences	
S-PYR Pyrolysis with GCMS (seq. #4)	Measurement: Chemical and isotopic analysis of gases evolved from samples as a function of temperature (EGA) and GCMS analysis of organics thermally released from sample. Experiment Sequence: Quartz cell cleaned in pyrolysis oven; Sample delivered to cooled cup; Sample heated from ambient to ~1000 °C in helium gas stream while evolved gases are monitored by QMS and TLS; GCMS analysis initiated using gases trapped during gas processing in previous step with detection by QMS and GC thermal conductivity detectors. Notes: 59 quartz cups allow this sequence to be repeated many times over the course of the landed mission. Cups can typically be reused several times.
S-DER derivatization (seq #2)	Measurement: Analysis of chemically derivatized polar compounds such as amino acids and carboxylic acids that would not otherwise be detected by GCMS. Experiment Sequence: Foil on metal cup in SMS punctured; Sample delivered to one-cup solvent extraction/derivatization cell; Sample cup moved to oven for thermal processing; venting of solvent; Thermal injection of derivatized compounds onto SAM GC traps; GCMS. Notes: 9 derivatization cups in SMS.
S-CMB combustion (seq #8)	Measurement: Analysis of carbon isotopes in carbon dioxide produced by combustion in oxygen. Experiment Sequence: Quartz cell cleaned in pyrolysis oven; Sample delivered to cooled cup; Sample combusted using oxygen gas; carbon dioxide produced analyzed by TLS for $^{13}C/^{12}C$ isotopic composition
Atmospheric Analysis Sequences	
A-DIR Direct Atmospheric Measurement (seq. #4)	Measurement: QMS and TLS Analysis of atmospheric chemical and isotopic composition and seasonal and diurnal variations in trace species abundance. Experiment Sequence: Atmospheric gas directed into SAM gas manifold; Analysis by QMS and TLS scans. Notes: Duration and number of day time operation may be limited by thermal and energy considerations.

Table 14, continued.	
A-ENR Atmospheric Enrichment (seq #5)	Measurement: QMS, TLS, and GCMS analysis of atmospheric trace species. Experiment Sequence: Atmospheric gas directed over SAM gas traps for enrichment of trace species; Gases released from traps and analyzed by GCMS for trace species. Notes: Direct TLS and QMS measurement also possible during this sequence.
A-MET Methane enrichment (seq #6)	Measurement: TLS methane analysis with SAM CSPL methane enrichment. Experiment Sequence: Atmospheric gas directed over SAM gas scrubbers and cold traps; Methane released into TLS for isotopic and abundance determination. Notes: Enrichment sequence may be repeated as necessary for improved methane detection sensitivity.
A-NGE Noble Gas Enrichment (seq # 7)	Measurement: Noble gas analysis with SAM CSPL noble enrichment. Experiment Sequence: Atmospheric gas directed over SAM gas scrubbers and cold traps; Noble gases analyzed in SAM QMS operated in static mode. Notes: Enrichment sequence may be repeated as necessary for improved noble gas detection sensitivity and precision in isotope measurements.
Calibration Sequences	
CAL-GAS In situ gas calibration (seq #9)	Measurement: Calibration gas sampled by QMS, TLS, and GCMS to check instrument performance and changes with time. Experiment Sequence: Gas from SAM calibration gas cell released into manifold; QMS and TLS scans; Fluorocarbons trapped on SAM trap; GCMS analysis of fluorocarbons. Notes: Enrichment sequence repeated on approximately a monthly basis.
CAL-SOL Solid sample in situ calibration (seq #3)	Measurement: Identical to S-PYR sequence but using internal calibration standard consisting of carbonate and/or fluorinated carbon compounds. Experiment Sequence: Metal cup containing sample opened by SMS foil puncture operation; Sample heated from ambient to ~850 °C in helium gas stream while evolved gases are monitored by QMS and TLS; GCMS analysis initiated to detect fluorocarbons thermally released from cup and trapped during gas processing in previous step; GCMS analysis. Notes: 6 solid sample calibration cups will be used during the landed mission to check instrument performance.

Table 15. SAM instrument characteristics

Quadrupole Mass Spectrometer	
Summary: QMS analyzes the atmosphere, gases thermally evolved from solid phase samples to sub ppb sensitivity. QMS is the primary detector for the GC and can operate in static or dynamic mode	
Mass range	2-535 Dalton (Da)
Detector dynamic range	$>10^{10}$ with pulse counting and Faraday Cup
Crosstalk	$<10^{6}$ adjacent unit mass channels (below 150 Da)

Tunable Laser Spectrometer	
Summary: Two-channel Herriott cell design spectrometer that provides high sensitivity, unambiguous detection of targeted species (CH_4, H_2O, and CO_2) and selected isotope ratios. One channel is at a wavelength of 3.27 µm for CH_4, and the second is at 2.78 µm for CO_2 and H_2O.	
sensitivity	Methane: 2 ppb direct Water: 2 ppm direct CSPL enrichment improves by ~100×
Isotopes	$^{13}C/^{12}C$ in methane; $^{13}C/^{12}C$ in CO_2; $^{18}O/^{16}O$ in CO_2 ; $^{17}O/^{16}O$ in CO_2
Isotope precision	Typically < 10 per mil

Gas Chromatograph	
Summary: GC separates complex mixtures of organic compounds into molecular components for QMS and GC stand alone analysis. Helium carrier gas is utilized.	
Injection	Injection from traps in the SAM manifold or from 3 GC injection traps incorporated into the GC subsystem
6 GC Columns	GC1; w/o trap; w/o TCD; MXT20 (C5-C15 organics) GC2; w/o trap; TCD; MXT5 (> C15 organics) GC3; trap; TCD; Carbobond (permanent gases) GC4; trap; TCD; ChirasilDex (chiral compound separation) GC5; trap; TCD; MXT CLP (C5-C15 organics) GC6; trap; TCD; MXTQ (C1-C4 organics/N/S compounds)
Detection Limit	10^{-11} mole

5 Mission Planning

The following sections describe the phases of the MSL mission, from launch through the end of surface operations. The timeline and primary activities are summarized for each phase. For the surface phase, these are accompanied by an overview of the various constraints on science operations and a description of mission scenarios that exemplify how science return can be optimized under them.

5.1 Launch, Cruise, Approach, and EDL Phases; Surface Initial Checkout Activities

The current baseline launch window for MSL extends from 25 November to 18 December, 2011. Entry, descent, and landing will occur between 6 August and 20 August , 2012. During the cruise to Mars, the spacecraft will perform trajectory correction maneuvers (TCMs) and undergo a series of checkout and maintenance activities. An initial payload health checkout, assessing postlaunch health and functionality, occurs as part of the first spacecraft engineering checkout. In addition, there likely will be at least one window for more comprehensive payload tests, including examples of routine instrument sequences, collection of calibration data, and limited cruise science observations (e.g., RAD). The last 45 days before landing comprise the approach phase, involving additional trajectory correction maneuvers. Entry, descent, and landing activities occur within ~15 minutes prior to touchdown on Mars. MARDI acquires its data set from heat shield separation through touchdown (< 2 minutes). 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. Surface science operations begin upon landing, though the first few (< 10) sols will include critical hardware deployments, spacecraft and payload checkout activities, and possibly a drive out of the region contaminated by the landing engines’ effluents.

5.2 Surface Operations Phase: Overview

MSL's primary mission spans one Mars year (669 sols or 687 Earth days) after touchdown. Science team activities would 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 some exceptions due to the ~10 sol post-EDL rover checkout, a ~20-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 that lead to the acquisition, processing, and analysis of a sample of rock or soil in the analytical laboratories. The nature of the landing site will influence the ratio of driving to sampling, especially if the site is a “go to” site, where the primary science targets are some distance from the center of the landing ellipse.

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. Battery capacity, RTG output, overnight battery recharge, and management of the state-of-charge over multiple sols, are all critical to science planning. The thermal limitations, including significant time and energy required to heat mast, arm, and mobility actuators, vary with both local time and season, and are more severe at higher-latitude landing sites, especially in the southern hemisphere which experiences winter at aphelion.

Most science activities will occur during daylight hours on Mars. Commands for the sol's activities are sent via the overnight orbiter telecom pass or direct-from-Earth at local midmorning on Mars. The rover would 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. Between midafternoon and the next morning on Mars, the science operations team on Earth would assess the downlink, plan the next sol's activities, and prepare the commands. Data that are not essential for next-sol planning would be returned during the overnight orbiter telecom pass. This basic framework allows approximately five hours for tactical science activities on Mars, though additional payload or rover operations can occur outside of this window if they are not critical to the next sol's planning.

For the first ~90 sols after landing, MSL project personnel will live on "Mars time", allowing the above framework to be executed every sol. For the rest of the mission, however, the start time of the prime shift on Earth will track Mars time, sliding forward from 6 AM until it reaches 1 PM. 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 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.

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.

Table 16 summarizes some of the key resources affecting operations and the required capability for each.

Table 16. A few of the resources that drive science operations and the required minimum capabilities during the design stage of MSL

Some Resources that Drive Science Operations	Required Capability
Energy Available for Science Activities	250 W hr / sol
Downlink Volume (two UHF passes)	250 megabits / sol
Rover Awake Time	6 hr / sol
Traverse Distance	50 m / sol
Note: The actual capability on Mars with the delivered flight rover may exceed the requirements for certain environmental conditions or other favorable conditions. The requirements may not be met during anomalous conditions. Science activities include rover traverses. A small fraction of the downlink volume will be used to transmit rover health and housekeeping data.	

5.3 Example Mission Scenarios

There exists an enormous variety of ways in which the mission may unfold, because of the unknown nature of the discoveries, the flexibility of the scientific payload, and the capabilities of the rover. However, in order to understand how science operations can be optimized given the constraints listed above, a set of example mission scenarios has been developed. These scenarios contain typical science activities that address the scientific goals of the mission, including driving and the use of all instruments. The goal is to demonstrate a representative surface mission that fits within the mission constraints, not to examine every conceivable use of the payload or rover.

The mission scenarios envision a logical sequence of scientific operations that repeats multiple times as the rover explores the region around its landing site. The rover performs a detailed examination of a number of distinct locations; specifically, targets occur 10 m apart in clusters separated by 1.5 km. The analysis of a target is assumed to consist of a traverse to a site of interest, remote sensing measurements to identify a target, a short approach drive to place the target within the robotic arm workspace, contact analyses to triage the target and determine whether to sample it, a set of activities that acquire rock or soil samples, process them, and deliver them to the analytical laboratory instruments, and finally, the analysis by those instruments.

For the purpose of the scenarios, each target is assumed to undergo the full set of activities, though in practice, each step is a decision point that can go forward or restart the process (e.g., if the contact analyses suggest the target is not worth sampling). Groups of activities with a similar goal, and which do not require any intermediate decisions from the science operations team, are collected into representative Sol Types. Overlain on these sols are systematic and opportunistic measurements by the environmental instruments. For example, on every Sol Type, REMS collects 1-Hz data for 5 minutes periodically throughout the day and night, while RAD observes for 15 min every hour, day and night. Most sol types also include one hour of passive DAN measurements and one additional hour-long block of REMS observations.

Traverse Sols are sols in which roving is the dominant activity. The scenarios use Traverse Sols to move the 1.5 km between clusters of targets. The roving capability is assumed to be 50 m/sol, but will vary with terrain, thermal constraints, and available energy. Traverse Sols begin with a set of targeted ChemCam observations. The roving goal is determined from engineering camera data (from a previous sol) as well as HiRISE imagery. Mastcam panoramas and DAN measurements are taken at intervals along the traverse. At the end of the traverse, the rover acquires Mastcam and Navcam panoramas, Hazcam stereo pairs, and a set of untargeted ChemCam observations.

Reconnaissance Sols initiate the detailed study of a site by returning remotely sensed "survey" observations that allow the science team to plan the next steps. Reconnaissance Sols begin with a set of targeted ChemCam observations, followed by an arm deployment (requiring Hazcam imagery from a previous sol), and acquisition of a MAHLI 3-D product. The remaining activities collect Mastcam and Navcam panoramas. The APXS remains deployed overnight for a long integration.

Approach Sols are used to place a target (e.g., part of a rock or a patch of soil) within the robotic arm's workspace and to prepare for workspace activities. The target is identified on a previous sol and can be reached in a single sol if it is less than ~10 m distant. Approach Sols begin with targeted ChemCam observations, a short APXS integration, and a MAHLI 3-D observation before the approach. After roving, Navcam and Hazcam images, and Mastcam spectral data, are collected within the workspace. DAN acquires active measurements during the approach and at the new location.

Contact Sols conduct scientific observations of a target with the arm-mounted instruments. A specific target selected from the approach data is analyzed with MAHLI and APXS. The target is then brushed and the measurements are repeated, though with a longer APXS integration. ChemCam and Mastcam take spectral observations to provide context to the target, while Hazcam images document the activities.

Sampling and Analysis Sols contain a set of activities with the end goal of placing solid sample material within CheMin and SAM. While it may be deemed unnecessary at some point, the scenarios presently assume that cross contamination is reduced in the drill and sample processing hardware by acquiring a "cleaning" sample before the "science" sample. First, a sample is acquired by the drill from a spot near the science target and fed through the appropriate sieve. Next, the primary sample is obtained, sieved, and delivered to CheMin and SAM. Remaining sample material, if available, is placed on the observation tray for analysis by MAHLI and APXS. Finally, CheMin and SAM complete their analyses. Unlike the other Sol Types that have activities thought to fit within a single tactical window on Mars, these activities will span 3 to 5 sols because of the required time, energy, and data volume. As a rule of thumb, sample acquisition, CheMin analyses, and SAM analyses each require at least one sol's worth of resources.

In addition to the activities in the above Sol Types oriented toward selecting and analyzing solid samples, there are many additional activities critical to achieving the mission's science objectives. Examples include the analysis of atmospheric gases by SAM, meteorological imaging, dedicated campaigns for REMS, RAD, and DAN, and calibration or cleaning activities for all instruments. These activities will be performed at the direction of the Science

Operations Working Group, in some cases taking advantage of sols not available for tactical commanding because of Earth-Mars phasing.

5.4 Mission Performance

Quantitative models of the above scenarios incorporate the operational constraints, the energy and data volume usages of the instruments and rover, and the time required to perform the activities. Nominal cases have been run along with special cases that assume high southern latitude, a go-to site, or resource limitations that are tighter or looser than presently expected. The modeling exercise has yielded insights on how to optimally plan each sol and how to exploit trades among resources to increase the science return. The modeling results quantify the scientific productivity of the rover at various sols throughout the year, and as integrated over the mission.

Two key measures of mission performance are the number of solid samples analyzed by the analytical laboratory instruments and the total distance traversed. The nominal mission performance model includes 25% margin (i.e., 1 in 4 sols) to account for potential increases in required time or energy, sols that fail to achieve planned outcomes, and communication problems. In addition, 40 sols are not available to science operations because they are used for health/maintenance activities or occur during solar conjunction. Finally, 150 sols are not commandable because of Earth-Mars phasing, occur during weekends after sol 180, and/or are dedicated toward science activities not involving the solid-sample-oriented Sol Types. The remaining 311 sols are used to perform the Sol Type scenarios at a reference landing site at 27°S. Given these assumptions, over its one Mars year primary mission, MSL is expected to be capable of selecting and analyzing 30 solid samples with a traverse of 4.5 km, or alternatively, selecting and analyzing 10 solid samples with a long "go-to" traverse of 15 km.

6 Mission Operations After Landing

After a short period of establishing the final surface configuration, and brief engineering checkout of the health of the rover, the science mission begins. The first approximately 90 days of the mission is accomplished with all operations participants on site at JPL working what is called “Mars Time,” with personnel shifting their work days 40 minutes forward each day to follow the Mars clock and personnel on duty 24 × 7. A description of how Mars Time operations worked for the Mars Exploration Rover mission is given in Bass et al. (2005) and Mishkin et al. (2006). Operating on Mars Time and extra staffing in 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. A major objective of this period is to develop the capability to complete the tactical one-sol turnaround process in 8 hours or less.

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. In the fully remote configuration, the science operations team will support 7 day per week tactical operations on Earth time (sliding between 06:00 and 20:00 Pacific time) for the second 90 days of the mission. Beyond that, for the rest of the mission, the operations team will support 5 day per week tactical operations on Earth time (multisol rover plans will be prepared for weekends and holidays).

Most science team roles can be fulfilled by using a phone or VOIP connection for teleconferencing and a PC, Mac, or Linux computer connected to the internet that is running JPL-provided software to allow data transfer, telemetry viewing, activity planning, and instrument sequencing. Scientists participating in operations are expected to bring their own laptop computer to JPL for Operations Readiness Tests and landed operations (running Windows 7, Mac OSX 10.6 or higher, or Linux Red Hat 5.3 or similar). The same type of computer can be used to participate in operations remotely from home institutions.

In the sections that follow, the roles and activities of science operations personnel are classified into two broad categories, tactical and strategic. Here tactical refers to the rapid turnaround of data analysis and rover commands in support of daily operation of the MSL rover. Strategic refers to longer term activities that guide the tactical process and refine the scientific results from the mission.

6.1 Team Structure

The overall flight team structure consists of these main groups: Management, Integrated Planning and Execution (IPE), Mission Design & Navigation, Real Time Operations, Engineering Operations, and Science Operations. Operations has two components: a tactical one (near-term work necessary to plan the upcoming sol or few sols) and strategic one (longer-term work). This division of operations work and general operations structure is similar to the structure used in operations for the Mars Exploration Rover (MER) mission as described in Mishkin et al. (2006). The MSL Science Operations Element of the Mission System consists of one team, the Science Operations Working Group (SOWG). The SOWG includes the instrument Principal Investigators, Co-Investigators, Collaborators, Participating Scientists, Project Scientist, Deputy Project Scientists, Program Scientist, Investigation Scientists, and other science operations personnel.

The MSL SOWG is responsible for:

- science data analysis, distribution, and archiving
- creation of the tactical activity plan
- instrument sequencing
- science instrument monitoring
- strategic science planning
- support of MSL outreach efforts
- timely publication of scientific results

6.2 Tactical Science Operations

The mechanism for generating and prioritizing rover and instrument science activities in support of science operations after landing on Mars will be through initiation by the Science Theme Groups (STGs) and deliberation in the Science Operations Working Group (SOWG) meetings. MSL science team members can belong to any one or more of the four MSL Science Theme Groups (Table 17). Each theme group will be composed of team members representing multiple instruments, working together to analyze scientific results and to prepare science activity plans that address their group's science objectives. In the SOWG Meeting, Science Theme Group leads (STLs) will present and advocate for their group's activity plan. In support of tactical operations, all science results and data (preliminary and updates) will be shared with the full science team, as soon as they become available (see Appendix B, MSL Science Team Rules of the Road). The SOWG Chair will lead the SOWG to a consensus on a tactical activity plan that meets the resource constraints and Long Term Planner strategic direction.

Table 17. MSL Science theme groups

Theme Group	Objectives
Organic Geochemistry and Biosignatures (BIO)	• 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 (MIN)	• Chemical, mineralogical, and isotopic composition of rocks and soils
Geology (GEO)	• Bedrock geology, geomorphology, and stratigraphy • Rock and soil textures • Rock and soil physical properties
Atmosphere and Environment (ENV)	• Meteorology and climate • Distribution and dynamics of water and dust • Solar, UV, and high-energy radiation • Atmospheric chemical and isotopic composition

Tactically, the science investigations of PI-led instrument teams and those of Participating Scientists will be advocated through participation in theme groups. Instrument-related concerns and advice will also be provided in SOWG meetings by the Payload Downlink and Payload Uplink Leads.

Science team tactical roles are described in Table 18 and tactical science operations meetings are described in Table 19. Participating Scientists are expected to actively participate in one or more theme groups. In addition, there will be opportunities for Participating Scientists to fill other tactical and strategic science team roles. Assignment to other roles is not expected until after joining the science team.

Table 18. Science team tactical roles

Role	Details
SOWG Chair	Lead the Science team in all tactical science meetings including the Science Kickoff and SOWG Meetings. Attend tag-up with Mission Manager and Tactical Uplink Lead prior to each SOWG meeting. Lead the science team to a consensus for daily planning during the SOWG meeting. Adjudicate when consensus cannot be reached. Follow the uplink process as the science representative to ensure science desires are maintained. During the single shift operations, responsible for verifying that all PUL sequences have been validated.
Science Uplink Representative (SUR)	Take over for the SOWG chair and documentarian part way through the uplink process during 16-hour operations (the first ~90 days). Represent science during the final stages of the uplink process and documents any changes to the science plan. Responsible for verifying that all PUL sequences have been validated. This role is merged with the SOWG chair during the 8-hour operations process (after ~the first 90 days of the mission).
SOWG Documentarian	Record discussions during the Science Kickoff Meeting, SOWG meeting, and any other discussions with SOWG Chair. Document the justification for why one observation request/activity was chosen over another and any scientific breakthroughs that result in operations-critical decisions. Follow the entire uplink process documenting the rationale for daily science plan and any changes to the science plan that occur in the uplink process.
Long Term Planner (LTP)	Present material during the Science Kickoff Meeting (16-hour ops) or the SOWG meeting (8-hour ops) that summarizes current rover activities, reviews liens, and presents a "sol path" that outlines activities in the near future. Ensures the tactical plan is in line with the strategic goals.
Science Theme Lead (STL)	Represent a specific theme group during Science Kickoff Meeting (16-hour ops) and the SOWG meeting. Responsible for advocating for STGs desired observations. Build STG plan fragment in MSLICE (MSL Operations InterfaCE), with assistance from other theme group members and deliver to Science Planner prior to SOWG meeting. Document process related to STG and broadcast to members.
Science Theme Group (STG) Member	Analyze critical science data products, developing and testing hypotheses. Support the preparation of the STL's representation of the STG science at the Science Kickoff Meeting (16-hour ops) and the SOWG Meeting. Work with the STL to decide on science observations to request in current sol and in developing a prioritized STG plan fragment.

Table 18, cont'd.	
Role	Details
Payload Downlink Lead (PDL) - instrument specific	Verify and monitor the payload health and status of all expected and received data products. Report this information, along with status/recommendation for instrument-specific consumables to SOWG. Recommend instrument performance check/diagnosis activities to the SOWG for incorporation into the science plan. Document the information, along with any assessments and recommendations to PULs/PDLs/SOWG in PDL report. Ensure production of any products necessary for tactical decision making (e.g., quick-look data products, preliminary interpretations, and preliminary derived data products).
Payload Uplink Lead (PUL) - instrument specific	Create, validate, and deliver instrument sequences. Assess the compatibility of payload commands with operational constraints, and modify them as necessary. Support and take direction from the SOWG Chair as necessary to ensure that modified activities are consistent with the SOWG's original intent. In SOWG meetings, provide instrument advice and ask questions to understand the intent of the activity plan. Document what happened during shift in PUL report.

Table 19. Science operations tactical meetings

Meeting	Description
Science Kickoff Meeting	The SOWG Chair leads this meeting, requesting a Long Term Planner report, instrument health updates from all the PDLs and a rover health update from the Mission Manager. The skeleton plan will be reviewed and then each STL is polled to determine their highest priority science observations for the sol and what they will bring forward to the SOWG meeting. Initial target decisions are made at this time so that either 1 clear target or a set of potential targets can be given to the Rover Planners for analysis prior to the SOWG meeting. In the 8-hour operations mode, the Kickoff meeting will be merged into the SOWG meeting.
Science & Engineering Tag-up	Formal tag-up prior to the SOWG meeting between the engineering leads and the SOWG Chair. This is where the Tactical Downlink Lead (TDL) alerts the Tactical Uplink Lead (TUL) of any engineering requests for the sol and the SOWG Chair learns of any restrictions on the rover applicable to the sol.
Science Operations Working Group Meeting (SOWG)	Main tactical meeting. The SOWG Chair leads this meeting and gets a rover status update from the MM, instrument updates from the PDLs, and any comments from Rover Planners about targets for that sol. Discussion about targets takes place if necessary. The TUL steps through the skeleton plan. The Science Planner will review and edit as necessary the tactical activity plan based on feedback from the STLs and Chair. Input from the sequencing team will be incorporated into the plan as appropriate. After science and engineering have approved the tactical activity plan, the PULs make any comments, and the plan is saved and ready to be passed to the IPE team.

Activity plans will be prepared using a data visualization, target selection, and activity planning software tool called MSLICE (MSL Operations InterfaCE), which is similar to the planning tool used for the MER and Phoenix missions (Bass and Talley, 2008). The MSLICE software will be provided to MSL science team members and can be run on PC, Macintosh and Linux laptops and desktop computers.

Tactical meetings are described in Table 19.

6.3 Strategic Science Operations

The PSG will give strategic (long-term) direction to the Long Term Planners (LTPs) and SOWG chairs. The Long Term Planners will develop the strategic plan for surface science. A complete list of strategic roles is given in Table 20, and description of strategic meetings is given in Table 21.

Table 20. Science team strategic roles

Role	Details
SOWG Chair	Work with Tactical Uplink Lead and Science Planner to prepare a skeleton/plan for the next sol. Ensure all liens or strategic issues are captured and understood by the LTP.
Long Term Planner (LTP)	Lead Science Discussions to discuss working hypotheses for recent results and overall mission results. Check with STL's individually (or in Science Discussions) to get their strategic planning inputs, and communicate relevant plan inputs from the other STGs. Strategic planning for immediate activities and "big" picture mission objectives. Work as a group (all the LTPs together) to update the Strategic Plan every month or so, as necessary. Expose the Strategic Plan to the full SOWG for feedback. Participate in PSG meetings to discuss strategic goals, explain the details/issues of the Strategic Plan to the PSG, and take strategic direction from the PSG. Participate in outreach activities.
Science Theme Leads	Work with, coordinate, and lead the STG to prepare for the next sol's planning. Provide inputs on the STG's long term plan options to the LTPs, find out about other STG inputs and relay relevant information back to the STG members. Participate in outreach activities.
Science Theme Group Member	Analyze science data products. Participate in Science Discussions when possible, coordinating presentation requests with the LTP. Support the validation of science data products for the Planetary Data System (PDS). Create special products for daily and weekly outreach reports, quick-release products, detailed scientific summaries, and public information releases including data captions. Participate in press conferences and outreach activities as needed. Publish results in scientific journals. Support long term science planning.
Principal Investigator (PI) - instrument specific	Oversee the operation of a specific instrument on MSL. Act as the point of contact with the MSL Project for strategic instrument issues. Ensure that the quality of the science measurements, instrument data products, and PDL/PUL interpretations allows the science team to fully address the MSL science objectives. Support the Strategic Plan, by providing inputs to LTPs on strategic instrument issues (recommended changes in use or consumables strategy). Participate in PSG meetings to discuss strategic goals and any operations concerns. Participate in press conferences and outreach activities. Ensure their instrument team's participation in the SOWG. Ensure all data are archived in the PDS.

Table 20, cont'd.	
Role	Details
Payload Element Lead (PEL) - instrument specific	Assist the instrument PI in meeting their responsibilities. Coordinate science operations associated with the specific instrument. The PI may delegate to a PEL the responsibility for PDL/PUL staffing, training, and scheduling, and PI-provided infrastructure support. The PEL may be on call for issues that cannot be solved by the PDL/PUL when the PI is unavailable. The PEL may be tasked to ensure that higher-level products are generated and shared with the Project. The PEL may be tasked to ensure that PDS archiving and Project data sharing meets the schedule.
Payload Downlink Lead (PDL) - instrument specific	Process and calibrate all data products received and make them available to the science team. Assess instrument performance long-term trends.
Payload Uplink Lead (PUL) - instrument specific	Support long term activity sequencing of instruments and suggest updates to the Activity Dictionary, as necessary.

Table 21. Science operations strategic meetings

Meeting	**Description**
Project Science Group Meeting	The PSG will convene on a daily to weekly basis, or as often as necessary (could be daily to weekly), to discuss strategic issues, staffing and scheduling of SOWG roles, use of consumables, press releases, and press conferences, etc. They will also prepare guidance for the Long Term Planners and SOWG Chairs to follow.
Science Discussion Meeting	The LTP leads this discussion where science team members are able to present science results, reach agreements about downlink data product re-prioritization requests, discuss working hypotheses, and talk about strategic plans. Daily meeting at the beginning of the mission, then later happening weekly or as needed.
PI Team Meeting	PIs will convene instrument team meetings to discuss strategies for operations, scientific hypotheses, and findings.
MSL Science Team Meeting	The MSL Project will convene an MSL Science Team Meeting approximately once every 6 months to discuss status, results, and strategies.

6.4 Pre-Landing Training and Operational Readiness Tests

Surface Operational Readiness Tests (ORTs) will be more beneficial to science team training than EDL ORTs, but EDL ORTs can be used to fulfill the required training. The exact number of trips and their durations and specific dates for training exercises will be negotiated between the Participating Scientists and the Project later, but must be consistent with the required minimum training necessary for participation in the rover operations and an updated Project schedule for operations tests. The following test schedule is preliminary and subject to change:

February 2012 Surface ORT: Traverse, Recon, Approach (5-7 day test)*
March 2012 EDL ORT: TCM-5, EDL, Surface Sleep with faults (2-3 day test)
April 2012 Surface ORT: Contact, Drilling, Analysis (5-7 day test)*
May 2012 Surface ORT: Contact, Drilling, Analysis with faults (5-7 day test)*
July 2012 EDL ORT: TCM-5, EDL, Preparation for drive (3-4 day test)

*Most relevant for science operations training

7 Archive Generation, Validation, and Transfer to the Planetary Data System

Appendix A of this document contains a draft MSL Archive Generation, Validation, and Transfer Plan. Table 4 in that document shows the current plan for what products will be archived in the Planetary Data System (PDS). Table 5 in Appendix A shows the schedule for public release of validated data by the PDS.

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Mars Science Laboratory
Archive Generation, Validation, and Transfer Plan
Initial Release DRAFT

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This document is included as Appendix A of the MSL Participating Scientist Proposal Information Package.

Mars Science Laboratory Project

Archive Generation, Validation and Transfer Plan

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CHANGE LOG

DATE	SECTIONS CHANGED	REASON FOR CHANGE	REVISION

ITEMS TO BE DETERMINED

SECTIONS	TBD ITEM	RESPONSIBILITY
2.3 Data volume	Data volume size estimates	Project, working with the DAWG
Table 4	TBD: RDR products to be defined for DAN	DAN team

CONTENTS

FIGURES

TABLES

ACRONYMS AND ABBREVIATIONS

AN	Analyst's Notebook
APXS	Alpha Particle X-ray Spectrometer
CCD	Charge Coupled Device
ChemCam	Chemistry & Micro-imaging
CheMin	Chemistry & Mineralogy
DACS	Data Acquisition and Command Subsystem
DAN	Dynamic Albedo of Neutrons
DAWG	Data Archive Working Group
DMT	Data Management Team
DSN	Deep Space Network
EDR	Experiment Data Record
FOV	Field of View
GC	Gas Chromatograph
GCMS	Gas Chromatograph/Mass Spectrometer
GDS	Ground Data System
Hazcams	Hazard Cameras
IFOV	Instantaneous Field of View
IKI	Institut Kosmitscheski Isledowani (Russian Space Research Institute)
IMU	Inertial Measurement Unit
JPL	Jet Propulsion Laboratory
LED	Light Emitting Diode
LET	Linear Energy Transfer, or energy absorbed per distance traveled by a given particle through a medium
MAHLI	Mars Hand Lens Imager
MARDI	Mars Descent Imager
Mastcam	Mast Camera
MPCS	Mission Data Processing and Control Subsystem
MSL	Mars Science Laboratory
MAC	Medium Angle Camera
NAC	Narrow Angle Camera
NAIF	Navigation and Ancillary Information Facility

Navcams	Navigation Cameras
NSSDC	National Space Science Data Center
OPGS	Operations Product Generation System
PDS	Planetary Data System
PI	Principal Investigator
PPI	Planetary Plasma Interactions
Pyr-QMS	Pyrolysis-Quadrupole Mass Spectrometer
QMS	Quadrupole Mass Spectrometer
RAD	Radiation Assessment Detector
RDR	Reduced Data Record
REMS	Rover Environmental Monitoring Station
RGB	Red Green Blue
RH	Relative Humidity
RTO	Real Time Operations
SA/SPaH	Sample Acquisition, Sample Processing and Handling
SAM	Sample Analysis at Mars
SIS	Software Interface Specification
SPICE	Spacecraft, Planet, Instrument, Pointing C-matrix, and Event kernels (historical acronym for navigation and ancillary data)
TBD	To Be Determined
TLS	Tunable Laser Spectrometer
UV	Ultraviolet
XRD	X-ray Diffraction
Z	Atomic number

1. INTRODUCTION

1.1 Purpose

The purpose of this document is to provide a plan for the generation, validation, and transfer of raw data sets and reduced data products acquired from the Mars Science Laboratory (MSL) Mission to the Planetary Data System (PDS). The archives will contain raw and reduced data, documentation, ancillary information, and algorithms or software.

1.2 Scope

Specific aspects addressed in this plan are:

- Generation of high-level mission, spacecraft and instrument documentation, instrument calibration reports, and documentation of algorithms and/or software used to produce reduced data records.
- Reduction of raw science data to generate reduced data records, including data sets expressed in geophysical units, with associated documentation that records when and where the data were acquired and for what purpose.
- Generation of SPICE kernels (files) used to support mission operations and in analyzing and labeling science data products.
- Generation and validation of archives containing MSL science and engineering data, software, algorithms, documentation, and ancillary information.
- Delivery to the PDS of validated MSL archives.

1.3 Contents

This plan begins with a summary of MSL mission phases and an overview of the archiving data flow. This section is followed by a description of the roles and responsibilities for organizations and personnel associated with generation, validation, and archiving of MSL data. The document ends with specific archiving plans.

1.4 Applicable Documents and Constraints

This Archive Generation, Validation, and Transfer Plan is responsive to the following Mars Exploration Program and MSL documents:

1. Mars Exploration Program Data Management Plan, R. E. Arvidson and S. Slavney, Rev. 3, March 20, 2002.
2. Mars Science Laboratory Downlink, Telemetry, and Data Management Functional Design Description MSL-376-1072, JPL D-34201.
3. Mars Science Laboratory Project Plan MSL-211-0201, JPL D-27144.
4. Mars Science Laboratory Mission Plan MSL-272-0211, JPL D-27162.

5. Mars Science Laboratory Science Office Management Plan MSL-214-0203, JPL D-27221.

The plan is consistent with the principles delineated in the following National Academy of Sciences reports:

6. Data Management and Computation, Volume 1, Issues and Recommendations, 1982, National Academy Press, 167 p.
7. Issues and Recommendations Associated with Distributed Computation and Data Management Systems for the Space Sciences, 1986, National Academy Press, 111 p.

The plan is also consistent with the following Planetary Data System documents:

8. Planetary Data System Archive Preparation Guide, August 29, 2006, Version 1.1, JPL D-31224.
9. Planetary Data System Data Standards Reference, March 20, 2006, Version 3.7, JPL D-7669, Part 2.

The plan requires the generation of the following Project documents:

10. Interface Control Documents between each instrument team and the relevant PDS Node.
11. Data Product Software Interface Specifications (SIS) for all Standard Products.
12. Archive Volume Software Interface Specifications (SIS) for all Standard Products.

Finally, the plan is meant to be consistent with the contracts and agreements negotiated between the MSL Project and each Principal Investigators (PI), in which reduced data records and documentation are explicitly identified as deliverable products.

2. MSL ARCHIVE GENERATION, VALIDATION, AND TRANSFER TO THE PDS

2.1 The Mission

The Mars Science Laboratory mission will deliver a rover to the Martian surface with the goal of exploring and quantitatively assessing a local region for evidence of past or present habitability. The rover will explore the landing site and acquire imaging, spectroscopy, and other measurements to characterize Martian soils, rocks, atmosphere, and other aspects of the environment. The rover will carry ten scientific instruments and a sample acquisition, processing, and distribution system. The various payload elements will be used as an integrated suite of tools to characterize the local geology, to study particular rock/soil targets, to acquire samples of rock, soil, or atmosphere for analysis in onboard laboratory instruments, and to characterize the local environment. The prime mission for the rover is expected to be 669-sols (approximately two Earth years), with the possibility of an extended mission of unknown duration after that. Figure 1 shows the mission timeline, as understood during the development phase of the Project.

The spacecraft that will be sent to Mars will consist of a cruise stage; an entry, descent, and landing system; and a rover. The ten science instruments can be classified into the following groups:

Mast-based remote sensing: Mounted on the top of a mast are the Mastcam multispectral imaging system provided by Malin Space Science Systems (PI: Michael Malin), and ChemCam, a laser-induced breakdown spectrometer and micro-imager provided by Los Alamos National Laboratory (PI: Roger Wiens).

Contact science: On the end of the robotic arm are APXS, an X-ray spectrometer provided by the Canadian Space Agency (PI: Ralf Gellert, Univ. of Guelph), and MAHLI, a hand-lens imager provided by Malin Space Science Systems (PI: Kenneth Edgett).

Analytical lab instruments: Located within the rover chassis are two analytical lab instruments. CheMin analyzes delivered solid samples using X-ray diffraction, and is provided by NASA Jet Propulsion Laboratory (PI: David Blake, NASA Ames Research Center). SAM analyzes solid or atmosphere samples using ovens, a gas chromatograph, mass spectrometer, and tunable laser spectrometer provided by NASA Goddard Space Flight Center (PI: Paul Mahaffy).

Environmental measurements: RAD is a radiation detector provided by Southwest Research Institute (PI: Don Hassler). REMS is a meteorology package provided by the Spanish Ministry of Science (PI: Javier Gomez-Elvira, Centro de Astrobiología/Instituto Nacional de Técnica Aeroespacial). DAN is an active neutron spectrometer provided by the Federal Space Agency of Russia (PI: Igor Mitrofanov, Space Research Inst. IKI). MARDI is a descent imager provided by Malin Space Science Systems (PI: Michael Malin).

Table 1 summarizes some of the key descriptive aspects of the MSL rover payload.

The sample acquisition, processing, and handling system (SA/SPaH) is designed to place and hold the contact instruments, to brush dust off rock surfaces, to acquire samples of rock and soil, and to deliver sample portions to the observation tray, analytical lab instrument inlets, or the ground. SA/SPaH consists of a robotic arm and turret, dust removal tool, rotary percussive rock drill, scoop, sieving and portioning device, and an observation stage mounted on the rover.

2.2 Data Flow

Several project documents describe the detailed functionality of key components of the data flow from instruments to the rover computer to Earth:

- MSL Telecommunications Functional Design Description (MSL-376-1070, JPL D-31499)
- MSL Downlink, Telemetry, and Data Management Functional Design Description (MSL-376-1072, JPL D-34201)
- MSL Flight-Ground Interface Control Document (FGICD) Volume 1: Downlink, (MSL-232-0219, JPL D-27356)
- MSL Ground Data System Functional Design Document (JPL D-36046, MSL 377-1437)

As indicated in Figure 3, each science instrument will generate its own data products which will be sent to the rover computer. The rover computer will turn those products into telemetry data products which also contain ancillary rover data. For surface operations, the primary data path will be for rover data products to be sent to an orbiter spacecraft (Odyssey or Mars Reconnaissance Orbiter) via UHF for later relay to the Deep Space Network (DSN) on Earth. An alternate path exists to send data directly to the DSN using the rover's X-band High Gain

Antenna. Then the Data Acquisition and Command Subsystem of the DSN will send relay pass products to the MSL Mission Data Processing and Control Subsystem (MPCS) which will build telemetry data products and send them to the OPGS (Operational Product Generation System) subsystem of the MSL Ground Data System.

The baseline process for science instrument data flow will be that the OPGS will generate Experiment Data Records (EDRs) from the science instrument telemetry data and SPICE data, assemble those EDR archive volumes, and deliver them to the PDS. In a few cases (indicated in Table 4), an instrument team (rather than the OPGS) will generate their own EDR products and deliver the EDR archive volumes to the PDS.

Reduced Data Records (RDRs) for the science instruments will be generated from EDRs, calibration data, and SPICE data by instrument teams, or by the OPGS if requested by an instrument Principal Investigator and successfully negotiated with the OPGS. The entity that generates the RDRs will also assemble them into archive volumes and deliver those volumes to the PDS.

The OPGS will generate EDR and RDR products for the engineering cameras (Navcams and Hazcams) and deliver those EDR and RDR archive volumes to the PDS. The OPGS will generate EDR products for SA/SPaH and the Rover Motion Counter and deliver those EDR archive volumes to the PDS.

The NAIF members of the MSL flight operations team will generate all SPICE kernels as well as maintain a web-based time conversion utility called chronos.

EDRs and RDRs will be generated according to designs specified in data product Software Interface Specification (SIS) documents that conform to PDS standards. Every MSL standard product will be described in a Data Product SIS. All MSL archive volumes will be assembled according to designs specified in Archive Volume SIS documents.

The Analyst's Notebook (AN) will be a repository for MSL science data products archived by the PDS. The AN will contain additional archive materials such as documentation, software, calibration data, engineering data, and SPICE kernels. Table 3 lists the high-level elements that comprise the MSL archives and Table 4 provides a preliminary list of all the individual data sets planned for archival.

Table 2 defines the different processing levels associated with data products. Most of the products listed in Table 4 are considered *standard products*, meaning that they are generated in a well-defined fashion on a regular schedule throughout the mission. In addition to the standard products in Table 4, *special products* may be generated by some data suppliers as time and other resources permit on an ad-hoc basis. Since special products are not part of the regular data processing, but rather are generated only as needed, they are not always described in SIS documents. Any special products that are completed and validated in time for a scheduled release to PDS may be delivered along with the standard products. PDS will continue to accept special products after the end of the mission as long as they are documented and validated according to PDS standards.

A data delivery may take the form of electronic transfer or delivery on physical media to the appropriate PDS Node (section 3.2). PDS personnel will work closely with science team members and OPGS to ensure a smooth transfer. When data products have been delivered to the PDS, they are regarded as publicly available. It is expected that the data will be promptly released to the public online through the PDS online distribution system, and through the Analyst's Notebook (section 2.6).

Online access will be the primary distribution method for MSL archives. The PDS is responsible for maintaining a long-term MSL archive and for delivering a copy of MSL archives to NSSDC according to agreements in place between the PDS and NSSDC.

2.3 Data Volume

For planning purposes, the total downlinked data volume from the expected 669-sol (1 Mars year) rover mission is estimated at approximately [TBD] gigabytes for the primary mission, based on sample mission scenarios. The total volume of EDR products after decompression is estimated to be the downlink volume times [TBD]. The total volume of RDR products is not yet determined, but could be as much as [TBD] times the EDR volume, which would correspond to a total archive data volume (EDR and RDR) of [TBD] terabytes. Extremely optimistic outcomes could result in two to four times as much downlinked data.

2.4 Data Validation and Peer Reviews

MSL science archives will be validated before being released to the PDS. Validation is accomplished in two parts: validation for scientific integrity and validation for compliance with PDS standards. Science team members are expected to conduct validation for scientific integrity in the course of their analysis of EDRs and their production of RDRs. The details of the science validation process are the responsibility of the instrument Principal Investigators.

Validation for compliance with PDS standards is also the responsibility of each Principal Investigator, with help from the PDS Node that will receive the data products. PDS will provide software tools, examples, and advice to help make this part of the validation as efficient as possible. This validation includes a Design Peer Review of the design and labeling of data products as laid out in the Data Product Software Interface Specification (SIS) documents, and validation of the PDS labels using sample data. The peer reviews for EDR and RDR products will take place well before the start of operations, to allow sufficient time to correct problems. Reviewers will consist of a small group of scientists who represent typical users of the data. The Investigation Scientist or Deputy Project Scientist assigned to the particular instrument and the relevant PDS node will also be represented on the review committee. The review period will last approximately three months and will be conducted mostly by email, culminating in a teleconference if needed. The result of the review will be a list of liens, or problems, that the PI must resolve before the product can pass the review. Another month (or more depending on the nature of the liens) will be allowed for the PI to address the liens. All liens should be resolved by six months before Mars landed operations. The goal is to allow the teams enough time to correct any problems before systematic generation of standard products begins.

After the start of operations, when generation of standard products has begun, each individual product will be validated by the PDS to see that it conforms to PDS standards and to the design specified in the SIS. Validation of individual products will be automated as much as possible. Data providers will be expected to correct errors found during the PDS validation.

2.5 Data Delivery Schedule

The MSL Level 1 requirements state that the Project shall archive copies of all verified, validated, and calibrated data acquired by the mission to the Planetary Data System within six months after its receipt on Earth. The MSL Project plans to make eight "batch" deliveries to the PDS, in 90 sol increments every 90 sols, starting with the first delivery 6 months after landing. In the event of an extended mission, subsequent data releases will continue at the same pace, with the final delivery occurring no later than six months after the last data have been received on Earth. Table 5 shows the dates for archive data acquisition and release for the primary mission.

2.6 Integrated Archives

The concept of integrated archives is the key to making the best use of the data returned by the various science instruments on MSL. In a rover mission, the instruments must operate in close coordination. Furthermore, a rover mission is non-deterministic; a decision to conduct a sequence of observations may be driven by recently acquired data rather than by a plan determined in advance. The general science community will require access to science data archives that are integrated across instruments by time, by location, and by observation target. Two complementary systems, the PDS Planetary Atlas (http://pdsimg.jpl.nasa.gov/search) and the Analyst's Notebook (http://an.rsl.wustl.edu), will provide the desired accessibility.

The PDS will offer other Web-based systems of access to MSL science data products using the PDS Planetary Atlas (http://pdsimg.jpl.nasa.gov/search) and PDS Data Set Search (http://pds.nasa.gov/). These web sites allow selection based on various search criteria, browsing of data, and downloading in various formats. These search interfaces will be available to the general science community for viewing and downloading data products that have been made public.

The Analyst's Notebook is a Web-based tool for correlating data products from various MSL instruments based on time, location, observation target, and other criteria. The Notebook will provide detailed views into operational decisions, results, and access to raw and derived data and instrument calibration information. Using the Notebook, a scientist can virtually replay mission events and science operations working group decisions, to better select and understand data products of interest. The Analyst's Notebook for MSL will be implemented by the PDS Geosciences Node in a fashion similar to the Analyst's Notebook for the Mars Exploration Rover (http://an.rsl.wustl.edu/). The Notebook for MSL will contain additional archive materials such as documentation, software, calibration data, engineering data, and SPICE kernels.

The PDS Planetary Atlas and the Analyst's Notebook are intended to be complementary tools. The Atlas will satisfy simple requests for locating and downloading data products by the general science community. The Analyst's Notebook will be used by scientists who need access to the most detailed information available or require more sophisticated display and searching capabilities. Together, the PDS Data Set Search, Planetary Atlas, and Analyst's Notebook will provide access to all MSL archived data.

3. ROLES AND RESPONSIBILITIES

In this section the roles and responsibilities for personnel and organizations involved in MSL archive generation, validation, transfer, and distribution are summarized.

3.1 Mars Science Laboratory Project Responsibilities

The MSL Project has overall responsibility for generation and validation of archives for release to the PDS. The Project Scientist co-chairs the Project Science Group and provides oversight of the archiving process from a science perspective. The Project Scientist will review data processing and analysis plans to assure timely and adequate analysis of spacecraft data and delivery of documented, complete data to the PDS. The MSL Mission System Manager, in coordination with the Project Scientist, is responsible for the administrative management of data archive planning and implementation.

The MSL Data Archive Working Group (DAWG) will coordinate the planning of the generation, validation, and release of PDS-compliant archives to the PDS. The DAWG reports to the PSG Co-Chairs (MSL Project Scientist and MSL Program Scientist). The DAWG Chair is an MSL Deputy Project Scientist. DAWG membership includes the MSL Project Scientist, the Principal Investigators and their archive representatives, representatives from NAIF and OPGS, and project personnel selected to ensure that engineering data sets and documentation are included in the archives. Representative PDS personnel will be liaison members of the DAWG. Most of the DAWG's work will take place before mission operations begin. During the active mission, the DAWG will meet as often as necessary.

The OPGS is responsible for generating Experiment Data Records (Level 0) for the MSL science instruments and for generating validated EDR and RDR archive volumes for the engineering cameras, except in the case of those instruments whose EDRs are generated by the instrument science teams (see section 2.2). The MSL Imaging Investigation Scientist will take the lead in validating the EDR and RDR products for the engineering cameras before delivery to the PDS and will be responsible for archiving calibration data and a calibration report for the engineering cameras.

NAIF members of the MSL flight operations team are responsible for generating validated SPICE kernels and delivering these to the NAIF Node of the PDS for archiving.

The instrument Principal Investigators are responsible for ensuring that PDS receives validated, PDS-compatible archives containing raw and derived data products from their instruments, along with documentation, algorithms or software for generating derived data products, calibration data and reports, and other supporting materials. In the case where a Principal Investigator negotiates with the MSL Project for OPGS to generate data products (and possibly assemble archive volumes and deliver them to PDS), the Principal Investigator is still ultimately responsible for the quality of the archive. The Project takes on the responsibility for timely delivery to PDS, with the exception of any required validation and required inputs from the PI.

The creation of some higher level data products may require the use of algorithms, models, or numerical simulations, for example. The documentation delivered to the PDS that describes these products must include a complete description of these techniques (and algorithms and/or software, when practical) in order to satisfy a reproducibility standard, as if the data products were published in a scientific journal. The calibration reports will be submitted to a scientific or technical journal, and the deliveries to the PDS will include references to those articles plus the calibration data.

3.2 Planetary Data System Responsibilities

The PDS is the designated point of contact for MSL on archive-related issues. The PDS is also the interface between MSL and the National Space Science Data Center (NSSDC). The PDS will work with the DAWG to ensure that the MSL archives are compatible with PDS standards and formats. Personnel from the PDS Geosciences, Imaging, Atmospheres, PPI, NAIF, and Engineering Nodes will be liaison DAWG Members.

The PDS will distribute and maintain MSL archives for the NASA planetary science community once the archives have been released by MSL. As noted in the Mars Exploration Program Data Management Plan:

> “A major objective of the PDS is to publish and disseminate documented data sets of use in scientific analyses. Whereas the media of the published data vary, all PDS-produced products are reviewed by scientists and data engineers to ensure that the data and the related materials are appropriate and usable. PDS data sets are typically published as archives, collections of reviewed data and documentation, ancillary information (such as calibration data), software, and any other tools needed to understand and use the data.”
>
> “PDS has developed a set of standards for describing and storing data so that future scientists unfamiliar with the original experiment can analyze the data using a variety of computer platforms with no additional support beyond that provided with the product.”

The Geosciences Node will provide overall coordination of PDS archive activities for MSL. The individual PDS Nodes will archive MSL data sets as designated in Table 4.

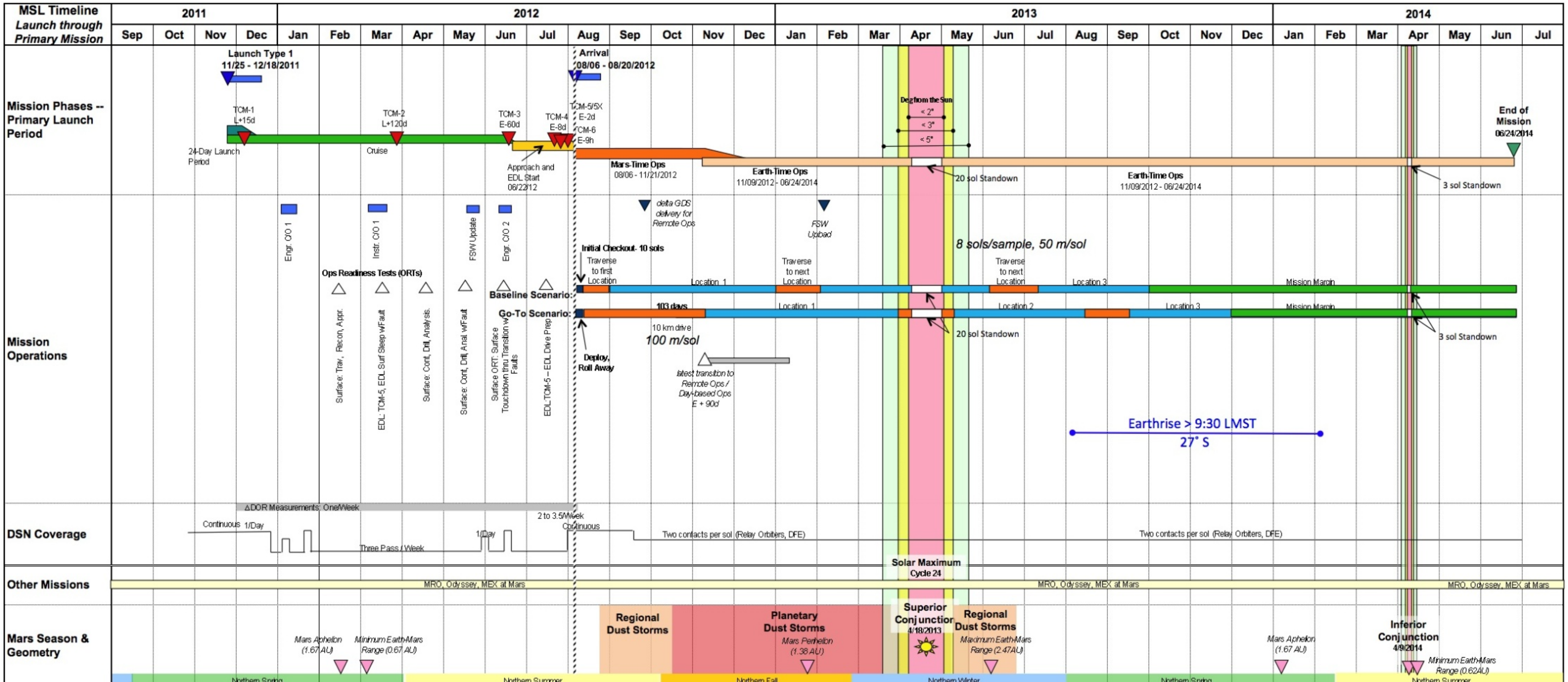
Primary responsibility for archiving MSL data will rest with the PDS Geosciences Node. The PDS Nodes involved with MSL data archiving will work together to archive data products from all of the MSL science instruments as a set of integrated archives using the PDS online services (e.g., Planetary Atlas and Analyst’s Notebook). The Imaging Node will archive MAHLI, MARDI, Mastcam, Navcam, and Hazcam data products; the Geosciences Node will archive APXS, ChemCam LIBS, CheMin, DAN, and SAM data products and rover engineering data; the Atmospheres Node will archive REMS data products; and the PPI Node will archive the RAD data products. The PDS NAIF Node will archive MSL SPICE files and will safe telemetry packets and related engineering files provided by the RTO team. SPICE files will also be included in the MSL integrated archives at the PDS Geosciences Node.

The Mars Data Engineer from the PDS Engineering Node will work with the PDS Discipline Nodes involved with MSL throughout the archive planning, generation, and validation phases.

3.3 National Space Science Data Center Responsibilities

The National Space Science Data Center will maintain a "deep archive" of MSL data for long-term preservation and for filling large delivery orders to the science community. The PDS will deliver at least one copy of MSL archive volumes to NSSDC. NSSDC may also provide support for distribution of MSL data to the general public, although this is beyond the domain of this data management plan

Figure 1. Mission Timeline, Type 1 Trajectory Launch Period



SOY	1	72	193	320	372	389	450	515	669	861	989
Sol #				1	34	90	150	205	364	558	669
Ls	0°	35°	90°	151°	180°	202°	240°	270°	0°	90°	151°
Date	09/14	11/25	03/30	08/06	09/30	11/06	01/07	02/24	08/01	02/15	06/24

Ls	0°	19°	104°	124°	162°	202°	224°	246°	276°	298°	314°	350°	0°	35°	102°	123°	151°
Date	9/14	10/22	4/30	6/13	8/27	11/07	12/12	1/16	3/05	4/09	5/07	7/12	8/1	10/13	3/15	4/29	6/25

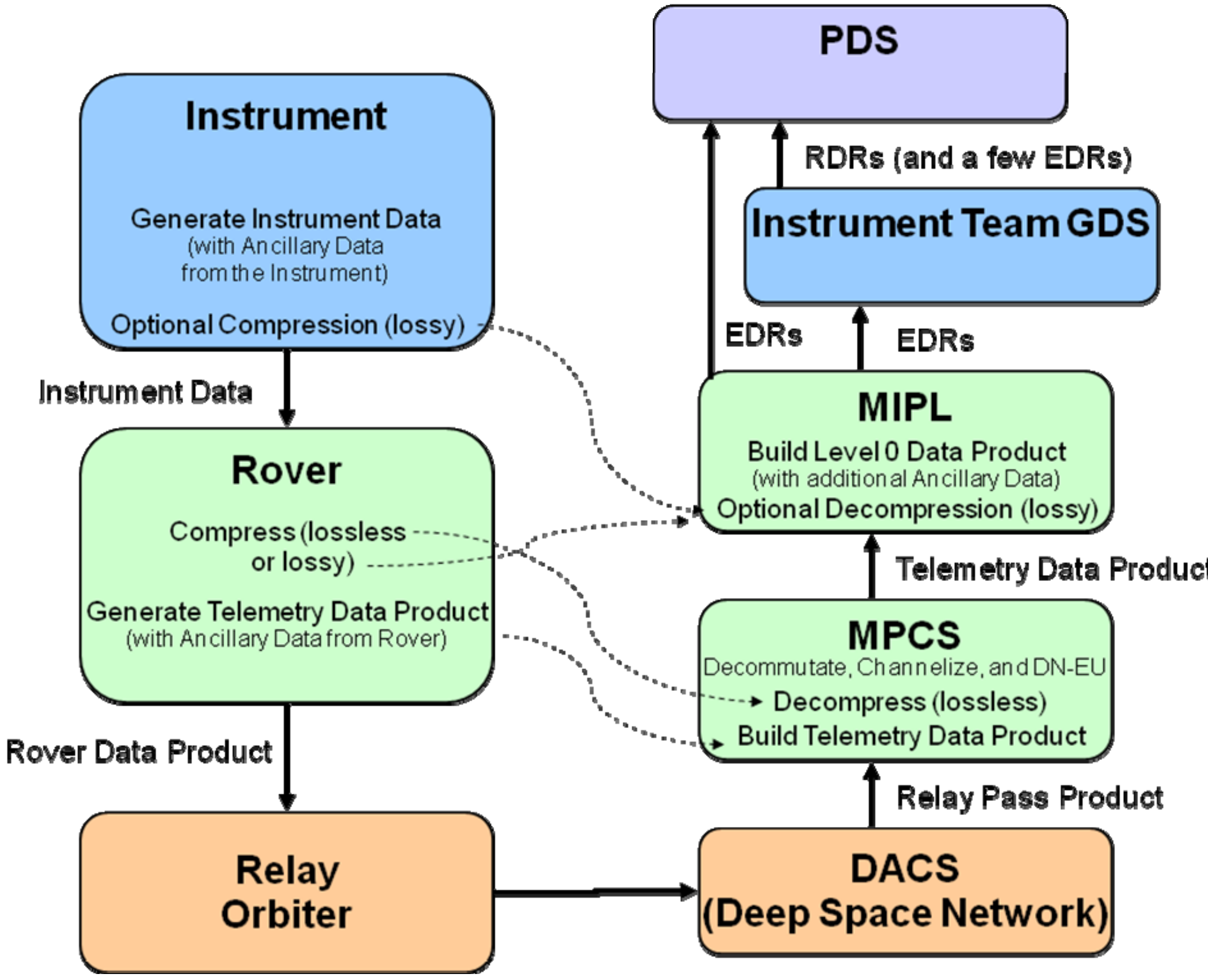


Figure 2. Baseline Downlink Data Flow for Science Instruments

Table 1. MSL Rover Payload and Engineering Cameras

Instrument	Key Parameters	Science Measurements
Mast-Based Remote Sensing		
Mastcam (Mast Camera)	Mastcam consists of two cameras, Mastcam-34 (M-34) with a 15° FOV and M-100 with a 5.1° FOV. Both have an integrated RGB Bayer pattern filter integrated over their detector for natural color plus narrow-band filters (430-1085nm range) for scientific color. 1200 × 1200 pixel images. The M-34 has 7.4 cm/pixel scale at 1 km distance and ~150 µm/pixel scale at 2 m distance. The M-100 has 450 µm/pixel scale at 2 m distance and 22 cm/pixel at 1 km. HD video at ~10 frames per second, 1280 × 720 pixels.	Observations of geologic structures and features. Studies of landscape, rocks, fines, soils, frost/ice, and atmospheric features.
ChemCam (Laser-Induced Remote Sensing for Chemistry and Micro-Imaging)	Laser induced breakdown spectroscopy measurements taken from a distance of up to 7 meters, 240-800 nm spectral range. Dust removal over a ~1-cm region. Depth profiling within a ~1-mm spot. High-resolution context imaging (0.08 mrad/pixel)	Rapid chemical composition (elemental abundances) of rocks and soils and high-resolution imaging from a distance.

Instrument	Key Parameters	Science Measurements
Contact Science		
APXS (Alpha Particle X-Ray Spectrometer)	X-ray spectroscopy using ^{244}Cm sources emitting alpha particles and X-rays. An energy dispersive X-ray detector provides X-ray spectra from 700 eV to ~25keV covering elements from atomic number Z= 11 to 35 and beyond. Measurement spot size when in contact with sample is ~1.5 cm.	Determination of chemical composition (elemental abundances) of rocks, soils, and processed samples.
MAHLI (Mars Hand Lens Imager)	Wide range of spatial resolutions, highest spatial resolution of 14 µm/pixel at 21 mm distance. Can focus at infinity. Returns natural color images, synthesizes best-focus images and depth-of-field range maps. Includes white light and UV LEDs for controlled illumination and fluorescence.	Close-up imaging of structure and texture of rocks, soils, fines, and frost/ice.

Instrument	Key Parameters	Science Measurements
Analytical Instruments		
CheMin (Chemistry and Mineralogy)	Powder X-ray diffraction. 2θ range ≥ 5-50°, 2θ resolution ≤ 0.35°, range of sensitivity: 1.1-10.0 keV, 600 × 600 pixel imager. Full-width at half-maximum intensity showing angular (2θ) resolution of better than or equal to 0.35 degrees, over the 2θ range from 24 to 45 degrees.	Identification, characterization, and abundances of minerals in rocks and soils.
SAM (Sample Analysis at Mars)	Quadrupole Mass Spectrometer: molecular and isotopic composition in the 2-535 Dalton mass range for atmospheric and evolved gas samples. Gas Chromatograph: resolves complex mixtures of organics into separate components. Tunable Laser Spectrometer: abundance and isotopic composition (precision < 10 per mil) of CH_4 and CO_2.	Identification and measurement of the abundances and isotopic ratios of organic molecules, potential biomarkers, and other atomic and molecular species in rocks, soils, and the atmosphere.
Environmental Measurements		
DAN (Dynamic Albedo of Neutrons)	Pulsing neutron generator and thermal and epithermal neutron detectors.	Measures the abundance of hydrogen (e.g., in water or hydrated minerals) within one meter of the surface.
MARDI (Mars Descent Imager)	Bayer pattern filter for natural color. Short exposure time to reduce image blurring from spacecraft motion. High-definition, video-like data acquisition (1600 × 1200 pixels, 5 frames per second)	Imaging of the landing region during descent.
RAD (Radiation Assessment Detector)	Solid state detector telescope and CsI calorimeter. Zenith pointed with 65º FOV. Detects energetic charged particles (Z=1-26), neutrons, gamma-rays, and electrons.	Measures galactic cosmic ray and solar energetic particle radiation, including secondary neutrons and other particles created in the atmosphere and regolith.

Instrument	Key Parameters	Science Measurements
REMS (Rover Environmental Monitoring Station)	1-Hz sampling rate for 5 minutes each hour. Ground temperature 150-300 K range, 2 K resolution. Air temperature 150-300K range, 0.1 K resolution. Vertical and 2-D horizontal wind speed. Pressure sensor range 1-1150 Pa, resolution 0.5 Pa. Humidity range 0-100%, 1% resolution, UV radiation detector with 6 bands over the 200 to 400 nm range.	Measures the meteorological and UV radiation environments: wind, ground and air temperature, pressure, humidity, UV radiation.
Engineering Cameras		
Hazcams (Hazard Avoidance Cameras), body-mounted in front and rear of rover	Monochrome CCD stereo imaging in front of rover and rear of rover, 2.1 mrad IFOV, 124° × 124° FOV; 1024 × 1024 pixel images	Imaging used for hazard avoidance during traverses and robotic arm deployment support. Also useful as science imaging of rocks and soils.
Navcams (Navigation Cameras), mast-mounted	Monochrome CCD stereo imaging, 0.82 mrad IFOV, 45° × 45° FOV; 1024 × 1024 pixel images	Imaging used for planning rover traverses. Also useful as science imaging of geologic structures and features, rocks, and soils.

Table 2. Definitions of Processing Levels for Science Data Sets

NASA	CODMAC	Description
Packet data	Raw – Level 1	Telemetry data stream as received at the ground station, with science and engineering data embedded.
Level 0	Edited - Level 2	Instrument science data (e.g., raw voltages, counts) at full resolution, time ordered, with duplicates and transmission errors removed.
Level 1A	Calibrated - Level 3	Level 0 data that have been located in space and may have been transformed (e.g., calibrated, rearranged) in a reversible manner and packaged with needed ancillary and auxiliary data (e.g., radiances with the calibration equations applied).
Level 1B	Resampled - Level 4	Irreversibly transformed (e.g., resampled, remapped, calibrated) values of the instrument measurements (e.g., radiances, magnetic field strength).
Level 2	Derived - Level 5	Geophysical parameters, generally derived from Level 1 data, and located in space and time commensurate with instrument location, pointing, and sampling.
Level 3	Derived - Level 5	Geophysical parameters mapped onto uniform space-time grids.
Level 4	Ancillary – Level 6	Ancillary data.

Table 3. Components of MSL Archives

Component	Contents
SPICE Archives	• SPICE Kernels
Science Data Archives	• Science Experiment Data Records and Reduced Data Records, including ancillary data in the data product headers • High-level mission, spacecraft, instrument, data set, software, and personnel descriptions for the PDS Catalog • Data Product Software Interface Specification (SIS) Documents • Archive Volume Software Interface Specification Documents • Processing Descriptions, Algorithms, and Software (to use in understanding reduced data product generation) • Instrument Calibration Plans and Reports and associated data needed to understand generation of calibrated data products • Analyst's Notebook • Science Operations Working Group Documentarian Notes and Mission Manager Notes (in the Analyst's Notebook)
Engineering Archives	• Sample Acquisition, Processing and Handling (SA/SPaH) EDRs • Engineering camera EDRs and RDRs • Rover Motion Counter

Table 4. List of MSL Data Products to be Archived

Product Name	NASA Level	Standard or Special	Description	Data Set Producer	Archive Volume Producer	PDS Curator
APXS EDR	0	Standard	Raw data, binary table	OPGS	APXS Team	Geosciences
APXS RDR		Standard	Description of target, e.g. target name, sample condition (as is, brushed, abraded, trench, wheel tracks)	APXS Team	APXS Team	Geosciences
APXS RDR		Standard	Derived sum of the sub X-ray spectra, shifted and selected (two columns: Energy(keV), counts)	APXS Team	APXS Team	Geosciences
APXS RDR		Standard	Derived elemental peak areas (counts per second) for standard elements (Na, Mg, Al, Si, P, S, Cl, K, Ca, Ti, Cr, Mn, Fe, Ni, Zn, Br) with statistical uncertainties	APXS Team	APXS Team	Geosciences
APXS RDR		Standard	Extracted oxide weight percents for standard element oxides with statistical uncertainties	APXS Team	APXS Team	Geosciences
APXS RDR		Special	Further trace elements with statistical uncertainties	APXS Team	APXS Team	Geosciences
APXS RDR		Special	Mineral norm	APXS Team	APXS Team	Geosciences

Product Name	NASA Level	Standard or Special	Description	Data Set Producer	Archive Volume Producer	PDS Curator
CHEMCAM EDR	0	Standard	Raw LIBS spectra, binary table	OPGS	ChemCam Team	Geosciences
CHEMCAM EDR	0	Standard	RMI raw images	OPGS	ChemCam Team	Geosciences
CHEMCAM EDR	0	Standard	RMI subframe images	ChemCam Team	ChemCam Team	Geosciences
CHEMCAM RDR		Standard	LIBS spectra calibrated with wavelength calibration	ChemCam Team	ChemCam Team	Geosciences
CHEMCAM RDR		Standard	LIBS element abundances, binary table	ChemCam Team	ChemCam Team	Geosciences
CHEMCAM RDR		Standard	RMI radiometrically corrected images	OPGS	ChemCam Team	Geosciences
CHEMCAM RDR		Standard	RMI geometrically corrected images	OPGS	ChemCam Team	Geosciences

Product Name	NASA Level	Standard or Special	Description	Data Set Producer	Archive Volume Producer	PDS Curator
CHEMIN EDR	0	Standard	Sampled raw frames	OPGS	CheMin Team	Geosciences
CHEMIN EDR	0	Standard	2-dimensional diffraction patterns (all counts)	OPGS	CheMin Team	Geosciences
CHEMIN EDR	0	Standard	2-dimensional diffraction patterns (single events)	OPGS	CheMin Team	Geosciences
CHEMIN EDR	0	Standard	2-dimensional diffraction patterns (split events)	OPGS	CheMin Team	Geosciences
CHEMIN EDR	0	Standard	EDS spectrum (all counts)	OPGS	CheMin Team	Geosciences
CHEMIN EDR	0	Standard	EDS spectrum (single events)	OPGS	CheMin Team	Geosciences
CHEMIN EDR	0	Standard	EDS spectrum (split events)	OPGS	CheMin Team	Geosciences
CHEMIN EDR	0	Standard	Stacked raw frames (film mode)	OPGS	CheMin Team	Geosciences

Product Name	NASA Level	Standard or Special	Description	Data Set Producer	Archive Volume Producer	PDS Curator
CHEMIN EDR	0	Standard	Modified raw frames	OPGS	CheMin Team	Geosciences
CHEMIN RDR	1	Standard	Background-corrected XRD data summed along 2-theta radii, adjusted for arc length, and presented as intensity vs. 2-theta tables (all events)	CheMin Team	CheMin Team	Geosciences
CHEMIN RDR	1	Standard	Background-corrected XRD data summed along 2-theta radii, adjusted for arc length, and presented as intensity vs. 2-theta tables (single events)	CheMin Team	CheMin Team	Geosciences
CHEMIN RDR	1	Standard	Background-corrected XRD data summed along 2-theta radii, adjusted for arc length, and presented as intensity vs. 2-theta tables (split events)	CheMin Team	CheMin Team	Geosciences
CHEMIN RDR	1	Standard	Background-corrected XRD data from the stacked raw frames, summed along 2-theta radii, adjusted for arc length, and presented as intensity vs. 2-theta tables	CheMin Team	CheMin Team	Geosciences
CHEMIN RDR	1	Standard	Background-corrected XRD data from modified raw frames, summed along 2-theta radii, adjusted for arc length, and presented as intensity vs. 2-theta tables	CheMin Team	CheMin Team	Geosciences
CHEMIN RDR	2	Standard	Mineral identification and abundances	CheMin Team	CheMin Team	Geosciences

Product Name	NASA Level	Standard or Special	Description	Data Set Producer	Archive Volume Producer	PDS Curator
DAN EDR	0	Standard	Raw data, binary table	OPGS	DAN Team	Geosciences
DAN RDR	1	Standard	TBD: Calibrated fluxes of neutrons	DAN Team	DAN Team	Geosciences
DAN RDR		Standard	TBD: Hydrogen abundance	DAN Team	DAN Team	Geosciences

Product Name	NASA Level	Standard or Special	Description	Data Set Producer	Archive Volume Producer	PDS Curator
Hazcam EDR	0	Standard	Raw Hazcam image data	OPGS	OPGS	Imaging
Navcam EDR	0	Standard	Raw Navcam image data	OPGS	OPGS	Imaging
Hazcam & Navcam RDR		Standard	Radiometrically corrected RDR	OPGS	OPGS	Imaging
Hazcam & Navcam RDR		Standard	CAHV linearized RDR	OPGS	OPGS	Imaging
Hazcam & Navcam RDR		Standard	Geometrically corrected RDR	OPGS	OPGS	Imaging

Product Name	NASA Level	Standard or Special	Description	Data Set Producer	Archive Volume Producer	PDS Curator
Hazcam & Navcam RDR		Standard	Stereo Correlation Disparity RDR	OPGS	OPGS	Imaging
Hazcam & Navcam RDR		Standard	Surface Normal RDR	OPGS	OPGS	Imaging
Hazcam & Navcam RDR		Standard	Range (distance) RDR	OPGS	OPGS	Imaging
Hazcam & Navcam RDR		Standard	XYZ RDR	OPGS	OPGS	Imaging
Hazcam & Navcam RDR		Standard	Surface Roughness RDR	OPGS	OPGS	Imaging
Hazcam RDR		Standard	Robotic Arm Reachability Map RDR (Hazcam only)	OPGS	OPGS	Imaging
Hazcam & Navcam RDR		Standard	Slope RDR	OPGS	OPGS	Imaging
Hazcam & Navcam RDR		Standard	Terrain "wedge" RDR	OPGS	OPGS	Imaging

Hazcam & Navcam RDR		Standard	Terrain "unified mesh" RDR	OPGS	OPGS	Imaging
Navcam RDR		Standard	Multi-frame Mosaic RDR (Navcam only)	OPGS	OPGS	Imaging
Hazcam & Navcam RDR		Standard	Range uncertainty estimate RDR	OPGS	OPGS	Imaging
Product Name	**NASA Level**	**Standard or Special**	**Description**	**Data Set Producer**	**Archive Volume Producer**	**PDS Curator**
MAHLI EDR	0	Standard	Raw images (including thumbnails and images from video sequences)	MSSS Team	MSSS Team	Imaging
MAHLI RDR	1	Standard	Radiometrically & geometrically calibrated images	MSSS Team	MSSS Team	Imaging
Product Name	**NASA Level**	**Standard or Special**	**Description**	**Data Set Producer**	**Archive Volume Producer**	**PDS Curator**
MARDI EDR	0	Standard	Raw images (including thumbnails and images from video sequences)	MSSS Team	MSSS Team	Imaging
MARDI RDR	1	Standard	Radiometrically & geometrically calibrated images	MSSS Team	MSSS Team	Imaging

Product Name	NASA Level	Standard or Special	Description	Data Set Producer	Archive Volume Producer	PDS Curator
MASTCAM EDR	0	Standard	Raw images (including thumbnails and images from video sequences)	MSSS Team	MSSS Team	Imaging
MASTCAM RDR	1	Standard	Radiometrically & geometrically calibrated images	MSSS Team	MSSS Team	Imaging
Product Name	**NASA Level**	**Standard or Special**	**Description**	**Data Set Producer**	**Archive Volume Producer**	**PDS Curator**
RAD EDR	0	Standard	Raw data, binary table, histogram counts per unit time	OPGS	RAD Team	PPI
RAD RDR		Standard	Proton flux (MeV/(cm^2*sr*sec))	RAD Team	RAD Team	PPI
RAD RDR		Standard	He flux (MeV/(cm^2*sr*sec))	RAD Team	RAD Team	PPI
RAD RDR		Standard	Neutron flux (MeV/(cm^2*sr*sec))	RAD Team	RAD Team	PPI
RAD RDR		Standard	Z>2 flux (MeV/(cm^2*sr*sec))	RAD Team	RAD Team	PPI
RAD RDR		Standard	Linear Energy Transfer (LET) (keV/µm)	RAD Team	RAD Team	PPI
RAD RDR		Standard	Dose Rate	RAD Team	RAD Team	PPI

Product Name	NASA Level	Standard or Special	Description	Data Set Producer	Archive Volume Producer	PDS Curator
REMS EDR	0	Standard	Raw telemetry data, all sensors	OPGS	REMS Team	Atmospheres
REMS RDR	1	Standard	Calibrated data, all sensors: Wind velocity and direction: (U,V,W) vector (m/s), ground temperature: T (K), air temperature: T1 and T2 (K), pressure: P (mbar), humidity: H (%RH), and six measurements of ultraviolet radiation: A, B, C, ABC, D, E (W/m^2)	REMS Team	REMS Team	Atmospheres
REMS RDR		Standard	Calibrated data, all sensors (with and without ancilliary data corrections): Wind velocity and direction: (U,V,W) vector (m/s), ground temperature: T (K), air temperature: T1 and T2 (K), pressure: P (mbar), humidity: H (%RH), and six bands of ultraviolet radiation: A, B, C, ABC, E, D (W/m2).	REMS Team	REMS Team	Atmospheres
Product Name	**NASA Level**	**Standard or Special**	**Description**	**Data Set Producer**	**Archive Volume Producer**	**PDS Curator**
RMC RDR	4	Standard	Rover Motion Counter: rover location and actuator move count	OPGS	OPGS	Geosciences

Product Name	NASA Level	Standard or Special	Description	Data Set Producer	Archive Volume Producer	PDS Curator
SAM EDR	0	Standard	Raw telemetry data combined with ancillary data on Rover position and orientation, SAM instrument suite state (power, temperature, etc.), atmosphere measurements (pressure, temperature), sample drill coordinates and related variables	OPGS	SAM Team	Geosciences
SAM RDR	1A	Standard	Unpacking of telemetry into data numbers and verification of data integrity	SAM Team	SAM Team	Geosciences
QMS L1B	1B	Standard	Quadrupole Mass Spectrometer: Pulse counter versus mass number, sorted by gas inlet	SAM Team	SAM Team	Geosciences
QMS L2	2	Standard	Quadrupole Mass Spectrometer: Gas composition; isotope ratios	SAM Team	SAM Team	Geosciences
GC L1B	1B	Standard	Gas Chromatograph: Total ion chromatogram vs. retention time; pressure; temperature; column used	SAM Team	SAM Team	Geosciences
GC L2	2	Standard	Gas Chromatograph: Species; relative abundance	SAM Team	SAM Team	Geosciences
TLS L1B	1B	Standard	Tunable Laser Spectrometer: Direct and demodulated spectra	SAM Team	SAM Team	Geosciences
TLS L2	2	Standard	Tunable Laser Spectrometer: Abundance and isotope ratios	SAM Team	SAM Team	Geosciences
GCMS L1B	1B	Standard	GCMS: Mass spectra data; smart scanning data; all data time tagged	SAM Team	SAM Team	Geosciences
GCMS L2	2	Standard	GCMS: Identification of pyrolysis products and derivatized compounds	SAM Team	SAM Team	Geosciences

Pyr-QMS L1B	1B	Standard	Pyrolysis: Pulse counter vs. mass, tagged with pyrolysis cell temperature	SAM Team	SAM Team	Geosciences
Pyr-QMS L2	2	Standard	Pyrolysis: Gas composition vs. sample temperature	SAM Team	SAM Team	Geosciences
Product Name	**NASA Level**	**Standard or Special**	**Description**	**Data Set Producer**	**Archive Volume Producer**	**PDS Curator**
SSP EDR	0	Standard	Sample Acquisition, Processing, and Handling (SA/SPaH) raw telemetry. Content not yet defined.	OPGS	OPGS	Geosciences

Table 5. MSL Archive Generation, Validation, and Release Schedule

Key Event	Date
MSL DAWG meetings begin	Feb , 2006
Preliminary EDR Software Interface Specifications (SIS's) and Archive Volume SIS's	Nov, 2010
EDR Design Peer Review (SIS's and example data products) begins	Dec, 2010
Preliminary EDR product generation software ready	Feb, 2011
EDR Design Peer Review ends	Mar , 2011
Preliminary RDR SIS's and RDR Archive Volume SIS's	Apr-May, 2011
RDR Design Peer Review (SIS's and example data products) begins	May, 2011
RDR Design Peer Review ends	Aug, 2011
Final EDR SIS's, Intermediate RDR SIS's and Final EDR product generation software	Sep, 2011**
Launch Date	Oct, 2011**
Intermediate RDR product generation software ready	Jan, 2012**
First surface Operational Readiness Test	Feb, 2012**
Final Instrument RDR SIS's and RDR product generation software	Jun, 2012**
Final EDR and RDR Archive Volume SIS's	Jun, 2012**
Data Product Delivery Test #1	Jul, 2012
Delivery Test #2 (optional)	Jul, 2012
Start of landed operations on Mars and beginning of data acquisition	Aug 6, 2012**
Delivery of validated products to the PDS for Release 1	Feb 6, 2013**
Public Release 1, data acquired on Sols 1-90	**Feb 27, 2013****
Delivery of validated products to the PDS for Release 2	May 9, 2013**
Public Release 2, data acquired on Sols 91-180	**May 30, 2013****
Delivery of validated products to the PDS for Release 3	Aug 9, 2013**
Public Release 3, data acquired on Sols 181-270	**Aug 30, 2013****
Delivery of validated products to the PDS for Release 4	Nov 14, 2013**
Public Release 4, data acquired on Sols 271-360	**Dec 15, 2013****
Delivery of validated products to the PDS for Release 5	Feb 17, 2014**
Public Release 5, data acquired on Sols 361-450	**Mar 10, 2014****
Delivery of validated products to the PDS for Release 6	May 19, 2014**
Public Release 6, data acquired on Sols 451-540	**Jun 9, 2014****
Landed operations on Mars completed (669 sols)	Jun 25, 2014**
Delivery of validated products to the PDS for Release 7	Aug 21, 2014**
Public Release 7, data acquired on Sols 541-630	**Sep 11, 2014****
Delivery of validated products to the PDS for Release 8	Nov 24, 2014**
Public Release 8, data acquired on Sols 631-669	**Dec 15, 2014****
Planned end of Project, if landed operations cease at 669 sols. Final release of any special products produced by the Project.	Jan 11, 2015**
If mission goes beyond 669 sols, future releases planned every 90 sols; final release no later than 6 months after end of mission.	
**Dates shown here are for the earliest possible launch date, and will be updated when they are better understood. The dates for delivery to PDS and PDS public release will shift accordingly, if the launch date shifts, with delivery of Release 1 = landing date plus 6 months, and date of Release N+1 = date of Release N + approximately 90 sols. Validated RDRs are delivered to the PDS 3 weeks before PDS public Release.	

Mars Science Laboratory
Science Team Rules of the Road
Revision B Release DRAFT

JPL D-34221
MSL-284-1387

December 13, 2010

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Jet Propulsion Laboratory
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Pasadena, California

This document is included as Appendix B of the MSL Participating Scientist Proposal Information Package.

Mars Science Laboratory Project
Science Team Rules of the Road

Approved by:

John Grotzinger, MSL Project Scientist Date

Michael A. Meyer, MSL Program Scientist Date

Concurred by:

David Blake, CheMin PI Date

Ralf Gellert, APXS PI Date

Paul Mahaffy, SAM PI Date

Igor Mitrofanov, DAN PI Date

Roger Wiens, ChemCam PI Date

Kenneth Edgett, MAHLI PI Date

Donald Hassler, RAD PI Date

Michael Malin, Mastcam and MARDI PI Date

Javier Gómez-Elvira, REMS PI Date

Jet Propulsion Laboratory
California Institute of Technology

CHANGE LOG

DATE	SECTIONS CHANGED	REASON FOR CHANGE	REVISION

TABLE OF CONTENTS

1 Introduction

1.1 Overview

The Mars Science Laboratory (MSL) scientific investigations will involve more than one hundred scientific participants: For example, there are 10 primary instruments, each with its own principal investigator (PI) and associated co-investigators (co-Is) and collaborators; additional participants will include the as-yet unselected participating scientists (PSs) and their associates; and there are many scientists and engineers at JPL with significant involvement in the project. 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.

The experiences of previous missions demonstrate that thinking through in advance how to manage the interactions and expectations of such a large and diverse group and getting "buy-in" from the leadership of the project to the approach to be followed is critically important. Although it is unlikely that all eventualities can be fully anticipated, the purpose of this document is to help ensure the orderly conduct of the MSL science investigation by specifying the principles and ground rules that will underpin the project's approach to managing the integrated scientific investigations of the MSL. A key aspect of this approach is to encourage and maximize the openness and transparency of interactions within the Project Science Group (PSG)[1] and the project as a whole.

1.2 Scope

This plan is an agreement among MSL science team members and collaborators (i.e., those listed in sections 6.1 and 6.2) starting from now and extending until six months after the end of surface operations of the MSL science investigation (note that this includes the possibility of an extended mission).

1.3 Revisions

This plan will be revised as needed to accommodate changes in the MSL science investigation. Revisions to sections 6.1 (MSL science team members) and 6.2 (MSL science team collaborators) will require the approval of the co-chairs of the PSG (the project scientist and the

[1] The PSG is co-chaired by the MSL project scientist and the MSL program scientist from NASA Headquarters and comprises the PIs as members. Additional scientists may be added to the PSG with the concurrence of the MSL project scientist and program scientist. 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. For any particular PSG meeting or discussion, a PSG member can send an alternate in their place.

MSL program scientist from NASA Headquarters) and will typically be proposed by a PSG member or a PS. All other revisions require the same approvals as the plan itself.

1.4 Related documents

Related documents include:

- MSL Science Office Management Plan (JPL D-27221, MSL-214-0203);
- MSL Archive Generation, Validation and Transfer Plan (JPL D-35281, MSL-214-1333); and the
- Mars Exploration Program Data Management Plan.

1.5 Relationship to Phase E Experiment Operations Plans (EOPs)

The Project recognizes that several components of these Rules of the Road including – but not limited to – the generation of higher level data products, release and archiving of data to public, etc., are dependent on funding resources provided through yet-to-be negotiated contracts. Signing this document implies an intent by the instrument teams to support and abide by the Rules of the Road, and an intent by the Project to provide adequate resources. If adequate resources are not made available in the Phase E or later contracts, allowable exceptions to the Rules will be noted in those contracts.

2 Scientific participants

2.1 MSL science team members

Each PI-led investigation comprises the PI, the co-Is, and the collaborators, and these groups are responsible for organizing themselves so as to optimize their activities. In this document, however, the science “team” embraces a larger group than an individual PI-led group. This is a key point in that it recognizes that achievement of the overall goals of the MSL will require integration of a wide range of geological, chemical, and physical observations and that the best chance of achieving these objectives will come from a “lumping” of the group into a single, interacting team rather than a “splitting” of it into isolated entities. Consequently, in this document we define the members of the MSL science team to include the PIs and co-Is of each PI-led investigation; the as-yet unchosen PSs; the project scientist and deputy project scientists; and the investigation scientists. A complete list of MSL science team members is provided in section 6.1 of this document.

2.2 MSL science team collaborators

Collaborators will in many cases be deeply involved in the scientific work of the project, but they have lower levels of responsibility to the project than science team members and consequently lower privileges. Most MSL science team collaborators will be specifically associated by name with a PI or PS; exceptions might include selected members of the MSL project staff at JPL as appropriate. Collaborators may either be specifically named on selected proposals or as-yet unnamed students, postdocs, and technical staff collocated with and working with team members. In all cases, the team member with whom the collaborator is associated is responsible for the collaborator understanding and accepting these Rules of the Road. A complete list of MSL science team collaborators is provided in section 6.2 of this document.

2.3 Additions and deletions of team members and collaborators

Addition of new team members and collaborators will be possible provided they have the approval of the co-chairs of the PSG (see section 1.3) and satisfy relevant NASA requirements (e.g., for foreign participants). New team members and collaborators will typically be proposed by a PSG member or a PS. Note that if team members or collaborators disassociate from the MSL project (e.g., by resigning), they are no longer bound by the MSL Rules of the Road provided the PSG agrees to release them from these rules, with the exception that they may not submit papers based on MSL data or otherwise release data to which they have had privileged access until the MSL project releases those data to the public. All additions and deletions of team members and collaborators will be reflected in timely updates to sections 6.1 and 6.2 of this document.

2.4 The science community

For the purposes of this document, the "science community" is defined to be all scientists who are not MSL science team members or collaborators.

3 Data privileges policies

Data privileges for all Mars Exploration Program missions, including MSL, are governed by the Mars Exploration Program Data Management Plan. We highlight here four types of data sharing and how they will be managed by the MSL project:

- *Data sharing within the MSL project*: Each investigation should have the capability to produce processed data products at their home institution and while at JPL (for example when collocated at JPL right after landing) and will provide them fully as soon as they are ready to the Ground Data System (GDS) for distribution project-wide to the entire science team and to the engineering operations teams. This is expected to be important for several reasons, including (1) guiding tactical operations (i.e., next-sol decision making); (2) strategic planning, which will require constant iteration based on knowledge of the full range of results across all investigations, and (3) maximizing the scientific benefit of the integrated MSL mission (i.e., immediate data-sharing across the entire science team will help with full interpretation of the data from all instruments). It will be the responsibility of individual PIs or PSs to distribute data and data products in a timely fashion to their collaborators. Note that it is expected that data processing and interpretation will evolve (e.g., from provisionally analyzed to fully validated and archivable data), and improved data products and interpretations will also be distributed within the project as they become available. 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 will release subsets of recent particularly interesting data or data products from each of the science instruments in a timely fashion. In addition, NASA, through the MSL project office, reserves the option to release or to direct the release of data or data products in support of public engagement.

Data not previously released to the public by NASA or MSL and/or inferences or interpretations based on such data may only be released by science team members based on specific approval by the PSG or through a PSG-approved-process for release approval; the PIs will have the primary responsibility for representing and coordinating their teams regarding such data releases. Note that these required approvals also apply to web sites maintained by team members, collaborators, and their institutions, as well as any release of information to the internet (e.g. blogs).

At the discretion of NASA Headquarters or the PSG, short-term embargoes on particular releases might occasionally be put in place (for example, in order to maximize the impact of a specific press conference or to comply with a particular journal publisher's request), but such embargoes are expected to be exceptions rather than the rule.

All images generated from the engineering cameras (i.e., the Navcams and Hazcams) will be made viewable by the general public 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 for any reason and will not require review or approval by anyone. However, given their rapid release, these images will typically be unvalidated and without complete ancillary information. It is not expected that other rover engineering sensor data will be released outside the science team until archived in the PDS or until included as outreach products by the project.

- *Release of data and discussion of interpretations through the media (print/radio/TV/film)*: Interviews of MSL science team members by the news media should be coordinated with the JPL Media Relations office. Each PI (and each science team member) may release data from their own instrument (or their own scientific investigations) to the press and discuss their interpretations through their home institution's media relations office, provided the releases and discussions are approved by the PSG and coordinated with the JPL Media Relations Office. Requests for such approval from team members are expected to be coordinated by the PIs, leaving at least several days advance notice for the approval. An important issue in interaction with the press will be to share credit appropriately within and across PI-led teams, and in giving its approval the PSG will take particular care to ensure such sharing.

  The PSG will work with JPL Media Relations to develop more detailed guidelines for science team members being interviewed in special situations, for members being interviewed at different levels of public exposure, and for members who have had different levels of media training. Public release of information about the mission's status will be coordinated with JPL Media Relations.

- *Data sharing with the science community*: It is NASA policy that investigators do not have exclusive use of data taken during the course of their investigation for any proprietary period. However, it is recognized that some time is required (no more than six months for the MSL project, as specified in the AO) for data products to be generated and validated. Consistent with this, PIs will be responsible for delivery of assembled and validated MSL data product volumes (Level 0 and 1 data, associated ancillary information, calibration data and information, and higher-level calibrated data products) to the PDS no more than six months after receipt on earth. Archive volumes should be PDS-standards compliant. The documentation delivered to PDS that describes the higher-level products must include a complete description (techniques, algorithms, calibration measurements, and/or software when practical) such that a reasonably skilled end user has enough information to fully understand and reproduce any 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 supplemental data associated with such publications) or products released to the general public as described in the MSL Archive Generation, Validation, and Transfer Plan and this Rules of the Road document. The importance of this cannot be overemphasized, and all team members and collaborators must be especially vigilant on this point; i.e., since we want everyone to be comfortable with complete openness within the project with respect to unpublished or incompletely processed or interpreted results, we must be especially careful not to violate the confidentiality of the group by broadcasting (even inadvertently) these hard-won data. An exception (see also section 4.2) is that selected results may be released to specifically chosen members of the community on an as-needed basis in order to enable their participation in the project when no team members or collaborators with adequate expertise are available (e.g., unanticipated results are encountered and no pre-selected team members or collaborators are experts in the area or have the time to devote to the new task); all such releases must be approved by the MSL project scientist, after consultation with the PIs responsible for the data and/or the PSG.

4 Publications

4.1 Overview – the role of the PSG

Peer-reviewed publication of the results of the MSL science investigation will be the primary means of reporting these results and their interpretations to the scientific community. Such publications will also likely be the primary basis for the professional recognition that scientists associated with the project will earn from their participation with MSL. Thus, clear guidelines for the preparation of journal articles and other professional communications are necessary, both to ensure effective communication of the results of the project and to ensure fair distribution of credit for these results and their interpretation. 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.

In view of the importance of the publication policy, its coordination and implementation will be the responsibility of the PSG. It is envisioned that decisions on what papers will be written, on authorship, on which results will be put in which of the papers, and so forth will be worked out within the PSG. This will give the PSG responsibility for coordinating the dissemination of the results of the project and the responsibility for balancing issues of equity and quality among the many participants in the project, especially as they relate to allocation of credit for obtaining and processing data, for creativity and the development of interpretations and hypotheses, and for scientific leadership within the project. In this context, the PSG will also have to respect divergent interpretations and, in particular, to encourage the publication of minority viewpoints (i.e., there will not likely be a monolithic project-wide interpretation of all the results) and the orderly publication of multiple interpretations of the same observations.

All team members and collaborators will be required to accept the decisions of the PSG on matters regarding publication, and, most critically, no science team member or collaborator shall knowingly participate in any publication of results or interpretations of MSL science data for the time period covered by these rules (i.e., until six months after the close of surface operations; see section 1.2) unless they have received specific authorization from the PSG to do so.

It is anticipated that the PSG will confer regularly to monitor the progress of manuscripts in preparation, to discuss plans for future publications and their authorships (including suggestions from any team member or collaborator for possible publications), and to coordinate the flow of publications. It is also important to emphasize that these decisions will not simply be reached by a majority vote; for reasons of academic freedom and the encouragement of maximum creativity, minority viewpoints shall be respected and protected. Thus, although the expectation is that most decisions will be achieved by consensus, it is likely that this will not always be possible. In these cases, it will be the responsibility of the project scientist to attempt to craft compromises that the PSG will accept. In those rare cases where no compromise that the entire PSG can agree to can be brokered, it will be the responsibility of the co-chairs of the PSG to make a decision. If one of the co-chairs has a personal stake in the outcome of such a decision, the decision will be made by the other co-chair.

4.2 Authorship guidelines

Authorship for all publications is open to all team members and collaborators, according to the following conditions:

- any team member who asks to be an author of any paper and who makes a substantive contribution to that paper (i.e., to the writing and/or to the research reported in the paper) shall be an author; and
- any collaborator who is invited by a team member to be an author on a paper and who makes a substantive contribution to that paper (i.e., to the writing and/or to the research reported in the paper) shall be an author.

Final decisions on authorship, both the inclusion or exclusion of people from the author list and the order of authors, will be made by the PSG as part of its coordination of the entire publication process, taking care to balance the issues discussed in section 4.1. Note that it is anticipated that many of the papers will involve team members and collaborators from several of the PI-led investigations. The appropriate authorship of papers will likely evolve during their preparation; the PSG-approved lead author of each paper will have access to the PSG to discuss issues of concern and will be responsible for keeping the PSG informed as to appropriate changes in authorship. The PSG will likewise be responsible for keeping the full project membership informed of all ongoing and anticipated publications.

As described in section 3, members of the science community may be authors (including lead authors, where appropriate) of a project-sanctioned paper only if:

- their participation on the paper (including the research leading up to the paper) has been pre-approved by the PSG based on a request from a team member; as described in section 3, approval by the PSG will be based on the judgment that the outside scientist brings to the investigation some unique and necessary capability not possessed by any team member or collaborator (or appropriate team members or collaborators are unwilling or unable to perform the work);
- they make major substantive contributions to the investigation and/or to the writing of the paper.

4.3 Anticipated publications

Although the actual schedule and nature of publications resulting from the MSL project will necessarily depend on events that cannot be fully predicted, we nevertheless anticipate that publication will take place in four phases: instrument descriptions, preliminary reports, detailed reports, and follow-on science.

- *Publications prior to landing*: Prior to landing, the project will publish an overview of its plans and capabilities. In addition, a series of papers in which each PI-led investigation will provide detailed investigation and instrument descriptions (including design and testing) will be published before landing; each instrument-specific publication in this series shall include an extensive description of calibration (unless a separate publication on calibration is prepared for that instrument). Note that it is expected that the author lists for these early publications describing instruments associated with a particular PI-led investigation will generally not include coauthors from other PI-led teams. It is also expected that papers with descriptions of other MSL investigations, hardware (e.g. SA/SPaH and its capabilities), and activities (such as field tests and landing site selection) will also be included in this set of publications.

- *"Preliminary" reports*: The MSL project will oversee the publication of a set of papers roughly analogous to the "30-day reports" of past missions, although they will not necessarily be written on a 30-day timescale (the actual time scale will be established by the PSG). They will be submitted to a peer-reviewed scientific journal that will provide timely publication. This set of papers will consist of one or more overview papers of key early findings, accompanied by a number of topical papers presenting these findings at a greater level of detail.

- *Detailed reports and other peer-reviewed publications*: After the publication of preliminary reports, the findings of the MSL science investigation will be published (generally in peer-reviewed journals) as appropriate. It is likely (but not required) that in addition to stand-alone papers, one or more sets of papers will be submitted as parts of special issues of journals. Planning and scheduling of these publications will be worked out by the PSG, but it is expected that there will be several coordinated waves of publications plus a steady stream of individual papers over the course of the project. As with all other publications during the course of the mission, the PSG will coordinate and oversee them. Note that with the passage of time (and especially if the mission has an extended lifetime and for publications that deal exclusively with data already released to the PDS), the coordination role of the PSG may in some cases outweigh the oversight role, but the roles of the PSG in keeping the team working together effectively; in keeping the full group aware of results, interpretations, and intended publications; and in ensuring fairness will continue throughout the lifetime of the project.

4.4 Presentations at scientific conferences

It is anticipated that results of the MSL investigation will be presented in forums such as scientific conferences. The PSG will have the responsibility to oversee and coordinate these presentations, and team members and collaborators wishing to make such presentations should request authorization from the PSG, leaving at least several days for advance approval. Authorship rules for such professional scientific presentations that take place within the time period covered by this document will be identical to those for peer-reviewed papers as stated in section 4.3, including those which are prepared and submitted prior to landing. For abstracts where it is appropriate for all team members to be coauthors but length limits prevent all from being listed, the phrase “the MSL science team” should be used.

4.5 Informal talks

Giving informal talks where abstracts are not required (e.g., departmental colloquia) is permissible by all team members and collaborators, and advance project-level approval is not generally required. However, notification of such talks should be provided to the project scientist, and for co-Is and collaborators, permission should be sought from their associated PI or PS. However, these presentations should not include data or results that have not previously been published (or distributed as part of a public release), archived in the PDS, or discussed at a scientific conference or workshop that included attendees not associated with the MSL science team.

4.6 Follow-on science

Follow-on science is any scientific research or publication after the time period covered by this document. The MSL science team will be considered to be disbanded after this time period, and there are no restrictions on any subsequent work by any team member or collaborator.

5 Operations policies

5.1 Integrated operations environment description

We anticipate that the mechanism for generating and prioritizing rover and instrument science activities for landed operations on Mars will be through initiation by the science theme groups or rover engineering team and deliberation in Science Operations Working Group (SOWG) meetings. Any MSL science team member can belong to one or more theme groups of their choosing. Each theme group will be composed of team members representing multiple instruments, working together to analyze scientific results and to prepare science activity plans that address their group's science objectives. In the SOWG Meeting, science theme group leads will present and advocate their group’s activity plan. In support of tactical operations, all science results and data (preliminary and updates) will be shared with the full science team, as soon as they become available (see Section 3).

Tactically, the science investigations of PI-led instrument teams will be advocated through instrument team members' participation in theme groups. Instrument-related concerns and advice will also be provided in SOWG meetings by the payload downlink and uplink leads. On a tactical basis, the PSG will delegate SOWG meeting decisions to the SOWG chair, although the mission manager can overrule the SOWG chair. In such cases, the SOWG chair can appeal to the project manager (PM) and project scientist (PS), but if the PM and PS are not available, the mission manager has the final say. On rare occasions, the PSG co-chairs or their designee may redirect the SOWG chair when the tactical plan compromises the PSG's strategic plan.

The PSG will develop the strategic (i.e., long-term) plan for surface science and will give strategic direction to the long term planners and SOWG chairs. For strategic issues involving engineering and spacecraft health, the project manager must be involved and can overrule the PSG. The PSG has the right to appeal such decisions to the Mars Program Office and Mars Exploration Program Director.

5.2 Inputs to activity planning

The PIs shall provide all project-requested input to the activity planning process for their instruments, including activity dictionary inputs, resource models, and parameters for expansion into sequences.

5.3 Participation in test and training

Instrument teams will make every effort to participate in appropriate prelanding development to support operations phase capabilities, including project-level test and training exercises.

5.4 Instrument uplink preparation

The instruments will be operated (command sequence generation and assignment of data downlink priority) in response to recommendations of the Science Operations Working Group to the MSL project, subject to approval by the MSL tactical uplink lead and mission manager.

5.5 Instrument use for engineering needs

Instrument activities advocated for engineering use will be given high priority when necessary (e.g., inspection of the rover or other instruments, traverse planning, sun finding, environment characterization, or other uses) as needed, on a limited basis, on any sol requested. Such requests will be transmitted through the Science Operations Working Group operations processes.

6 Personnel lists

6.1 Science team members

The following individuals are the members of the MSL science team[2]:

MSL Project Science Office

Anderson, Robert C. JPL (SA/SPaH Investigation Scientist)
Behar, Alberto JPL (DAN Investigation Scientist)
Blaney, Diana JPL (ChemCam Investigation Scientist)
Brinza, David JPL (RAD Investigation Scientist)
Crisp, Joy JPL (MSL Deputy Project Scientist)
de la Torre Juarez, Manuel JPL (REMS Investigation Scientist)
Grotzinger, John Caltech (MSL Project Scientist)
Maki, Justin JPL (MastCam, MAHLI, MARDI Investigation Scientist)
Meyer, Michael NASA Headquarters (Program Scientist)
Vasavada, Ashwin JPL (MSL Deputy Project Scientist)
Yen, Albert JPL (CheMin and APXS Investigation Scientist)

APXS

Campbell, Iain Univ. of Guelph (Co-I)
Gellert, Ralf Univ. of Guelph (PI)
King, Penny Univ. New Mexico and Univ. of Western Ontario (Co-I)
Leshin, Laurie NASA Headquarters (Co-I)
Lugmair, Guenter UC San Diego (Co-I)
Spray, John Univ. New Brunswick (Co-I)
Squyres, Steven Cornell Univ. (Co-I)
Yen, Albert JPL (Co-I)

ChemCam

Blaney, Diana JPL (Co-I)
Bridges, Nathan APL (Co-I)
Clark, Benton Space Science Inst. (Co-I)
Clegg, Sam LANL (Co-I)
Cremers, David Applied Research Associates, Inc. (Co-I)
d'Uston, Claude IRAP (Co-I)
Herkenhoff, Ken USGS (Co-I)
Kirkland, Laurel LPI (Co-I)
Langevin, Yves Institut d'Astrophysique Spatiale (Co-I)
Mangold, Nicolas LPGN (Co-I)
Manhes, Gérard Inst. Physique du Globe de Paris (Co-I)

[2] Names in bold indicate Project Science Group (PSG) members.

Mauchien, Patrick CEA (Co-I)
Maurice, Sylvestre IRAP (Co-I and Deputy PI)
McKay, Christopher Ames Research Center (Co-I)
Newsom, Horton Univ. New Mexico (Co-I)
Poitrasson, Franck GET (Co-I)
Sautter, Violaine LMCM, Museum Natl. Hist. Nat. Paris (Co-I)
Vaniman, David LANL (Co-I)
Wiens, Roger Craig LANL (PI)

<u>CheMin</u>

Anderson, Robert JPL (Co-I)
Bish, David Indiana Univ. Bloomington (Co-I)
Blake, David F. Ames Research Center (PI)
Chipera, Steve Chesapeake Energy (Co-I)
Crisp, Joy JPL (Co-I)
DesMarais, David Ames Research Center (Co-I)
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Farmer, Jack Arizona State Univ. (Co-I)
Feldman, Sabrina JPL (Co-I)
Gailhanou, Marc CNRS (Co-I)
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Ming, Douglas JSC (Co-I)
Morris, Richard JSC (Co-I)
Sarrazin, Philippe inXitu (Co-I)
Stolper, Ed Caltech (Co-I)
Treiman, Allan LPI (Co-I)
Vaniman, David LANL (Co-I and Deputy PI)
Yen, Albert JPL (Co-I)

<u>DAN</u>

Behar, Alberto JPL (Co-I)
Boynton, Bill Univ. Arizona (Co-I)
Kozyrev, Alexandre S. Space Research Inst. (Co-I)
Litvak, Maxim Space Research Inst. (Co-I and Deputy PI)
Mitrofanov, Igor G. Space Research Inst. (PI)
Sanin, Anton B. Space Research Inst. (Co-I)

MAHLI, MARDI, and MastCam

Bell, James F. III Cornell Univ. (Co-I)
Cameron, James Lightstorm Entertainment Inc. (Co-I)
Dietrich, William E. UC Berkeley (Co-I)
Edgett, Kenneth S. MSSS (MAHLI PI)
Edwards, Laurence Ames Research Center (Co-I)
Hallet, Bernard Univ. Washington Seattle (Co-I)
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Heydari, Ezat Jackson State Univ. (Co-I)
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Lemmon, Mark T. Texas A&M (Co-I)
Maki, Justin JPL (Co-I)
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Minitti, Michelle E. Arizona State Univ. (Co-I)
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Parker, Timothy J. JPL (Co-I)
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Torre Juarez, Manuel de la JPL (Co-I)

SAM

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Cabane, Michel LATMOS (Co-I)
Coll, Patrice Univ. Paris, LISA (Co-I)
Conrad, Pamela GSFC (Co-I and Deputy PI)
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Gorevan, Stephen Honeybee Robotics (Co-I)
Jakosky, Bruce Univ. Colorado Boulder (Co-I)
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Ming, Douglas JSC (Co-I)
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6.2 Science team collaborators

The following collaborators are associated with MSL science team members:

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Brunet, Claude CSA
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CheMin

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Brunner, Will   inXitu
Chemtob, Steve   Caltech (student of Albert Yen)
Hoehler, Tori   Ames Research Center
Wilson, Mike   Ames Research Center

MAHLI, MARDI, and Mastcam

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Bean, Keri   Texas A&M (student of Mark Lemmon)
Cantor, Bruce   MSSS
Caplinger, Michael   MSSS
Harrison, Tanya   MSSS
Jensen, Elsa   MSSS
Kennedy, Megan   MSSS
Lipkaman, Leslie   MSSS
Nixon, Brian   MSSS
Posiolova, Liliya   MSSS
Ravine, Michael   MSSS
Rice, Melissa   Cornell Univ. (student of James F. Bell III)
Sandoval, Jennifer   MSSS
Shean, David   MSSS
Supulver, Kimberley   MSSS
Williams, Amy   Univ. Calif. Davis (student of Dawn Sumner)
Zimdar, Robert   MSSS

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Israel, Guy CNRS
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McAdam, Amy GSFC
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Person, Alain LBES, Univ. Pierre & Marie Curie
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Tan, Florence GSFC
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MARS EXPLORATION PROGRAM

DATA MANAGEMENT PLAN

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This document is included as Appendix C of the MSL Participating Scientist Proposal Information Package.

Mars Exploration Program
Data Management Plan

Approved by:

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Planetary Data System

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Orlando Figueroa **Date**
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Mars Exploration Program, NASA Headquarters

Joseph H. King **Date**
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Tables

Figures

Changes

Date	Section	Change
5/20/99	6.1, Data Rights and Release Policy	Added paragraph VII
5/20/99	6.3, Data Release Acknowledgement Policy	New section
5/28/99	6.2, Public Information Release Policy	Added paragraph VI
6/21/99	6.1, Data Rights and Release Policy	Paragraph VII: added “immediately”
6/21/99	6.2, Public Information Release Policy	Paragraph VI: added “immediately”
6/21/99	2, Overview of the Mars Surveyor Program; Signature page; Acronyms	Removed “Mars Exploration Directorate”; added “Space Science Exploration Division”.
8/26/99	Signature page	Replaced Thomas E. Thorpe with Richard Cook. Added Chris Jones. Changed title for Daniel J. McCleese.
9/13/99	Signature page	Added Joseph Boyce.
4/11/00	6.1, Data Rights and Release Policy; 7, Documentation Concerning Returned Samples	Incorporated several edits by J. Boyce
4/11/00	Signature page	Changed PDS Project Manager from Rosana Borgen to Elaine Dobinson
11/2/00	6.1, Data Rights and Release Policy; 7, Documentation Concerning Returned Samples	Removed 4/11/00 edits by J. Boyce
11/2/00	All	Changed "Mars Surveyor Program" to "Mars Exploration Program"; removed references to MSOP; updated references to current and future missions
11/2/00	Signature page	Replaced Mars Surveyor Program personnel with Mars Exploration Program personnel
1/22/02	Signature page	Updated names
1/22/02	Table 1	Added MRO Specifications
1/23/02	Acronyms	Deleted MECA, MIP; Added IDS
1/28/02	Figure 1	Corrected mission phase lengths
1/28/02	Figure 3	Revised data flow
1/28/02	Table 4, 5	Updated outlines
1/28/02	All	Responded to review comments
1/29/02	Section 5.6, Data Set Documentation	Added PDS Catalog file responsibilities
3/20/02	Signature page	Added Garvin and McCleese

Acronyms

APXS	Alpha-Particle X-ray Spectrometer
ASI/MET	Atmospheric Structure Instrument/Meteorology Package
CD-ROM	Compact disc read only memory
CODMAC	Committee on Data Management and Computation
DAWG	Data and Archive Working Group
DSN	Deep Space Network
EDR	Experiment Data Record
GRS	Gamma Ray Spectrometer
IMP	Imager for Mars Pathfinder
IR	Infrared
JPL	Jet Propulsion Laboratory
MAG/ER	Magnetometer / Electron Reflectometer
MARCI	Mars Color Imager
MARIE	Mars Radiation Environment Experiment
MEP	Mars Exploration Program
MFEX	Microrover Flight Experiment (AKA: Rover, Sojourner)
MGS	Mars Global Surveyor
MOC	Mars Orbiter Camera
MOLA	Mars Orbiter Laser Altimeter
MPF	Mars Pathfinder
NAIF	Navigation and Ancillary Information Facility
NASA	National Aeronautics and Space Administration
NSSDC	National Space Science Data Center
PDS	Planetary Data System
PMIRR	Pressure Modulator Infrared Radiometer
PSG	Project Science Group
RDR	Reduced Data Records
SDVT	Science Data Validation Team
SIS	Software Interface Specification
SPICE	Spacecraft, Planet, Instrument, C-matrix, Events
TES	Thermal Emission Spectrometer

1 Purpose and Scope of Document

The Mars Exploration Program (MEP) Data Management Plan presents a high-level plan for timely generation, validation, and delivery of data products from MEP projects to the Planetary Data System (PDS) and the National Space Science Data Center (NSSDC) in complete, well-documented, permanent archives. The Plan also specifies policies and procedures for distributing the data and information to the general public in a timely fashion.

This document is for use by personnel associated with MEP projects to understand data release policies and how data products are to be archived. In fact, each Project will write an Archive Plan that is responsive to this document. Principal Investigators associated with MEP projects will use this document to understand what is expected of them in terms of delivery of a complete data archive, and how the PDS can help them prepare their data products. PDS and NSSDC personnel will use this document to understand the types of data products and archives they can expect to receive from MEP projects, in order to allocate resources accordingly.

2 Overview of the Mars Exploration Program

MEP is a multiyear effort with the intent of implementing a coordinated exploration of Mars. The focus is on understanding current and past climates, searching for evidence of past and extant life, and determining the extent to which human expeditions to the planet are feasible.

Implementation consists of launches during opportunities approximately 2-years apart (Figure 1). Mars Global Surveyor was the first project, followed by the 2001 Odyssey Orbiter. Future opportunities will include a pair of Mars Exploration Rovers to be launched in 2003 and the Mars Reconnaissance Orbiter in 2005. Scouts, orbiters, rovers, and sample return missions form the template for opportunities beyond 2005.

Science payloads for approved MEP Projects are listed in Table 1. The long-term scientific payoff of MEP will come about if the observations and resultant data feed from one project to the next and if documented archives are used by the scientific community to increase knowledge about the planet.

3 Overview of the Planetary Data System

The NASA PDS is an active archive that provides high quality, usable planetary science data products to the science community (Arvidson and Dueck, 1994, McMahon, 1996). This system evolved in response to science community requests for improved availability of planetary data from NASA projects through increased scientific involvement and oversight. PDS provides access to data archives for scientists, educators, and the public.

The first objective of the PDS is to publish and disseminate documented data sets of use in scientific analyses. Whereas the media of the published data vary, all PDS-produced products are reviewed by scientists and data engineers to ensure that the data and the related materials are appropriate and usable. PDS data sets are typically published as archives, collections of reviewed data and documentation, ancillary information (such as calibration data), software, and any other tools needed to understand and use the data. PDS provides access to data by a system of online and compact disc archives.

The second objective of the PDS is to work with projects to help them design, generate, and validate their data products as archives. The advantage of having projects deliver well-documented products is that use by the scientific and public communities is maximized.

The third PDS objective is to develop and maintain archive data standards to ensure future usability. PDS has developed a set of standards for describing and storing data so that future scientists unfamiliar with the original experiment can analyze the data using a variety of computer platforms with no additional support beyond that provided with the product. These standards address structure of the data, description of contents, media design, and a standard set of terms (PDS Standards Reference, 1995; Planetary Science Data Dictionary, 1996).

The fourth PDS objective is to provide expert scientific help to the user community. Most of the archive products may be accessed or ordered automatically by users, but PDS also provides teams of scientists to work with users to select and understand data. In some cases, special processing can be done to generate user-specific products. In addition, PDS-funded scientists provide a sounding board to the science community to for comments on the need for new and/or improved software, data sets, and archives.

To accomplish the four objectives, the PDS is structured as a distributed system composed of eight teams, called nodes (Figure 2). The science nodes include the Atmospheres, Geosciences, Planetary Plasma Interactions, Rings, and Small Bodies Nodes. Each has an advisory group of discipline scientists to provide guidance and priorities for PDS. The support nodes are the Imaging Node, with expertise in sophisticated image processing and cartography, the Navigation and Ancillary Information Facility (NAIF) Node, specializing in observation geometry and sequence of events information, and the Central Node, leading the project, at the Jet Propulsion Laboratory.

4 Roles and Responsibilities

This section summarizes the roles and responsibilities for personnel and organizations involved in the generation, validation, transfer, and distribution of MEP archives.

4.1 Mars Exploration Program

Each MEP project is responsible for the production and delivery to PDS of documented archives that use PDS standards. Instrument Principal Investigators are responsible, under contractual obligation, for working with PDS personnel on planning, generating, and validating archives from their instruments. The Project Science Group (PSG) will coordinate plans for archiving through such entities as a Data and Archive Working Group (DAWG) and the Science Data Validation Team (SDVT). Archives must include at least three copies on hard digital media produced under Project auspices and destined for long-term storage at PDS and NSSDC sites, in addition to any on-line transfers.

Each MEP project will generate an archive plan document that describes the specific generation, validation, and transfer to PDS of the project's data products. The plan will specify the contents of archives, the personnel or organization responsible for generating each archive, estimates of the amount of data to be delivered, and a schedule for delivery. The Project archive plans will be based on the policies and procedures specified in the Mars Exploration Program Data Management Plan (this document). An outline of a project archive plan is provided in Table 2.

Each MEP project is responsible for distributing its data products internally, i.e. among scientists associated with the project. If this distribution takes the form of a mass production of validated archive volumes (e.g. CD-ROMs), the PDS may ask to fund a number of additional copies for its own distribution, thereby saving production setup costs.

The Project Office of each MEP project is responsible for ensuring that the policies and implementation plans concerning release of information and interactions with the public and press are followed. The Project also is responsible for primary interactions with NASA Headquarters, including ensuring that Headquarters personnel are aware of information releases before they occur, and focusing feedback from Headquarters back to the appropriate parties. The Project has the responsibility for primary interactions with the JPL Media Relations Office, serving as coordinating entity for media relations focused at JPL.

The Project Scientist has primary responsibility for ensuring that scientific findings are made available to the media. In addition, the Project Scientist or his/her designates, working with the JPL Media Relations Office, will:

a. Help instrument teams prepare plans for generation and release of public-oriented data and results.

b. Ensure that PSG members prepare release materials with enough lead time so that NASA Headquarters receives the materials about a week before the general release to the media.

c. Coordinate the preparation of materials (press releases, interviews, press conference scripts, video file productions, etc.) with the JPL media relations representative.

d. Identify themes or subjects for each media interaction opportunity months in advance, and to schedule the preparation work.

e. Decide what the best media interaction vehicle should be for the information to be presented.

f. Help enforce the graphical standards of the Media Relations Office for best television viewing.

4.2 Planetary Data System

The PDS is the primary organization within NASA responsible for archiving and distributing planetary data. The PDS is thus the designated point of contact for MEP projects on archive-related issues. The PDS is also the interface between MEP projects and the NSSDC.

The PDS Geosciences Node Director has been selected to take the lead in working with each MEP project to ensure that overall plans are in place and that individual projects are meeting archiving commitments. Relevant PDS personnel will participate in archive planning efforts through DAWGs and the SDVT for each project to ensure that: (a) archives are planned, generated, and reviewed using PDS standards, (b) archives are constructed in ways that facilitate cross-mission and cross-instrument data analyses, (c) PDS provides user services that allow search and access to data in ways that transcend particular instruments or data sets.

The PDS is responsible for distributing MEP project archives to the broad science community after the data have been released by the project. Distribution may be done electronically via the Internet or by replication of archive volumes for delivery to users. The PDS maintains copies of project archives, and the relevant PDS discipline nodes are available to provide information and expert assistance to users of the data.

4.3 National Space Science Data Center

The NSSDC's primary role is to maintain a "deep archive" of data for long-term preservation, for filling any large orders requested by the science community, and for filling orders requested of the NSSDC by the general public. The PDS will deliver at least one hard medium digital copy of MEP project archive volumes to NSSDC.

4.4 Jet Propulsion Laboratory Media Relations Office

The JPL Media Relations Office is chartered to be the prime point of contact with the public and the media for activities focused at JPL. The overall objective of the Media Relations Office is to maximize the positive impact of information releases from the project. This office helps organize and implement press releases and press conferences. They facilitate release of data and information meant for consumption by the press and public, including video feeds of interviews.

4.5 Principal Investigator Home Institution Media Relations Offices

Each Principal Investigator may release findings from his or her instrument to the press, through the home institution media relations office, if those releases are coordinated with the MEP Project Scientist and the JPL Media Relations Office.

5 Data Products

The science-related data products to be produced during MEP projects are described in this section, including standard products, engineering and other ancillary products, and documentation that accompany data sets as they are delivered to the PDS. For reference, Table 3 defines numerical processing levels, using the common assignments developed by the NASA community.

5.1 Packetized Data Records

These data records consist of time-ordered packetized telemetry received from the spacecraft, with duplications removed, together with ancillary information needed to understand what is contained in a given packet.

5.2 Experiment Data Records

Experiment Data Records (EDRs) are NASA Level 0 products (see Table 3) and consist of time-ordered sequences of raw science data obtained by a given instrument, together with engineering information that allows instrument teams to check operation of their instruments. The specific contents of EDR data will be instrument-dependent.

5.3 Standard Data Products

Standard Data Products include both EDRs and Reduced Data Records (RDRs). RDRs are typically generated from EDRs and SPICE data at investigator facilities. RDRs are defined during the proposal and selection process and are contractually promised by the Principal Investigators as part of the investigation. Standard Data Products are produced in a systematic way during the course of the project, primarily by Instrument Teams, although some may be generated by Interdisciplinary Scientists addressing specific scientific problems. Standard Data Products are sometimes called operational products in other projects, since they are produced routinely with fairly well-defined procedures. During MEP projects it is expected that increased knowledge of instrument calibrations and operating nuances, together with increased knowledge of Mars, and better understanding of how to reduce raw data, will result in updates to some Standard Data Products.

Standard Data Products shall be delivered to the PDS in PDS-compatible format, including PDS labels and documentation. The documentation shall be thorough enough to understand quantitatively the processing history.

5.4 Ancillary Files

5.4.1 SPICE Files

SPICE is an acronym used to describe a suite of elemental ancillary data sets, often called kernels:

S Spacecraft Ephemeris, with files containing spacecraft location as a function of time

P Planetary/Satellite ephemerides and associated target body physical and cartographic constants

I Instrument information, including mounting alignment and field-of-view size/shape/orientation

C Orientation of a spacecraft's primary coordinate systems and possibly angular rates as well

E Event information, including nominal sequences, real-time commanding, unscheduled events, and experimenter's notebook comments

Most SPICE kernels will be generated by flight operations teams with some instrument information and sequence data obtained from instrument teams. Where appropriate, there will be both predict and reconstructed SPICE files. Reconstructed SPICE kernels will typically be generated within a couple of weeks after data acquisition and made available to instrument teams. SPICE kernels will be used together with a toolkit of software modules (to be supplied by JPL's Navigation and Ancillary Information Facility) at investigator institutions to generate the derived ancillary data needed to help plan observations and to process EDRs (see: NAIF, 1988). SPICE kernels and NAIF toolkit software are applicable to landers and rovers as well as to orbiting spacecraft.

5.4.2 Engineering and Other Data

Engineering data, while not strictly science data, can be used to aid the interpretation of science data and as such will be archived. Other data that may be useful include sequence of events files, log files, DSN monitor files, etc. The specific content of engineering and other ancillary data products will be negotiated between each Project and the PDS and incorporated into the Project Archive Plan. These products will be archived by NAIF or another entity as designated in the future. In some cases, engineering data may be bundled with science archives, e.g. rover wheel currents and rover yaw, pitch, and roll data would be needed to infer soil properties during traverses and trenching operations. Thus, these engineering data might be included in archives focused on imaging and *in-situ* data acquired during rover operations.

5.5 Public Information Products

Public Information Products consist of selected data products that have been annotated for the media with explanations and delivered to the relevant NASA or home institution offices for use in public relations. It is expected that these products will be produced mainly at investigator institutions, although hard copies for press distribution may be produced at JPL.

5.6 Data Set Documentation

Documentation of data acquisition and processing histories is crucial to successful long-term use of project data. The SPICE E Kernel will contain information delineating why data sets were acquired, including whether they were part of a coordinated sequence. Information on spacecraft events that affected the sequences and data products will also be included. The actual (as opposed to predict) SPICE files will be transferred to a long-term archive along with raw and reduced data.

Information needed to fully understand EDRs, SPICE files, and reduced data will also be generated for long-term use of MEP project data. Documentation to be provided by each instrument team will typically include:

- Calibration Requirements Document
- Calibration Report
- In-flight Calibration Report
- Science Reports
- User's Guides that describe data products from particular instruments and how they were generated
- Software User's Guides that describe processing software delivered as part of the archive
- Instrument-specific sequence of events, in E-kernel format

Documentation to be provided by each Project will include a Mission Operations Report, stipulating how the mission plan was actually carried out.

Data sets archived with PDS are described by entries in the PDS Catalog. Data set providers are required to supply descriptive information for the PDS Catalog. Specifically, the Project is responsible for descriptions of the mission and the instrument hosts (spacecraft), and instrument teams are responsible for descriptions of their instruments and data sets.

5.7 Software

It is expected that standard data products delivered by Principal Investigators should be in a format that is accessible by other users. If the products cannot be accessed using commonly available software tools, then the products should be accompanied by software or detailed algorithms that allow a user to access the data.

6 Policies for Release of Data and Public Information

6.1 Data Rights and Release Policy

Because of the expected widespread scientific and public interest in new results from Mars and the strong MEP commitment to releasing data on a timely basis, it is important to establish a clear release policy for archives and other data sets (e.g. quick-look products).

A key element of the policy is the need for a reasonable interval of time to generate and validate standard data products and archive volumes before release to the general community. Based on numerous past experiences (including the Magellan, Clementine, and MGS projects), up to a six-month period is necessary to produce useful RDRs for data from most instruments. EDRs and RDRs should be produced, validated, and released as soon as possible, with the six-month period considered to be a maximum (although certain data sets such as global maps may require more time to generate).

Specific release policies are:

I. The generation/validation time period for standard data products is defined to be the period from receipt of science packets containing raw data at instrument processing facilities until release of archive volumes to the PDS. The archive volumes will include, as appropriate, standard data products, SPICE files, relevant software, and documentation describing the generation of the products. During the generation/validation period, Instrument Teams are expected to use raw data to generate standard products and archives, and to validate the products and volumes. Efforts involving all of the project investigators are expected to be underway during this period, including product validation. Generation and validation of products and archives may typically require up to six months from the time of receipt of raw data at instrument processing facilities in order to produce and validate useful archive volumes. More rapid release is highly desired.

II. To ensure rapid dissemination of new and significant information, each Principal Investigator will also release a significant subset of data earlier as a form of public outreach and education. These releases will typically be available within a week of data receipt. Postings on the Internet (e.g., World Wide Web) will be used as a cost-effective way for widespread dissemination of these special products. The posted data may include images, derived spectra, topographic information, and other forms of data that illustrate new and significant results. Postings will include documentation. These data releases will conform to the Public Information Release Policy (section 6.2 below).

III. During the generation/validation period, use and analysis of raw and derived products from a particular instrument, use of the results of unpublished papers derived from such analysis, or use of data posted on the Internet for public outreach and education should be done only with the agreement of the relevant Principal Investigator.

IV. After the six-month or less generation/validation period, the relevant archive volumes will be transferred to the PDS, which will make them available to the general science community.

V. Individual Instrument Teams are strongly encouraged to make data available as soon as possible, and they may decide to make a number of versions available to the PDS on a more timely basis than the typical six-month period. They may not release data from other instruments.

VI. Items I. to V. above pertain to nominal mission operations. In the event of anomalies, such as the prolonged aerobraking phase for MGS, data should be archived using stated policies, unless observational, personnel, and/or financial constraints force the need for a longer period between data receipt and transfer of archives to the PDS.

VII. MEP reserves the right to require a Principal Investigator to acquire and/or release immediately a limited set of data for purposes of mission planning and ensuring mission safety, for both current and future missions.

6.2 Public Information Release Policy

Public information release includes press conferences and written material concerning both mission operations and scientific analyses. Specific policy statements for Public Information Release for Mars Exploration Program projects are:

I. Information concerning spacecraft and instrument anomalies may be released only by the Project Office, in coordination with NASA Headquarters and Principal Investigators.

II. Information concerning significant scientific results may be released during press conferences, press releases organized by the Project Office and the Jet Propulsion Laboratory's Media Relations Office, and on the World Wide Web, in coordination with NASA Headquarters and relevant members of the project's science teams.

III. Information concerning scientific results from a given instrument may also be released by the Principal Investigator for the instrument. For example, such releases may be organized by the home institution of the Principal Investigator. These releases can be in any medium, but significant results must have prior coordination through the JPL Project Office and NASA Headquarters.

IV. Information concerning scientific results from instrument studies may be released by an Interdisciplinary Scientist, Participating Scientist, or Co-Investigator before it is deposited in the Planetary Data System, only with the concurrence of the Principal Investigator whose instrument data are used.

V. In cases II through IV the Project Office must receive, in advance of the release, a copy of the release material (e.g., images, spectra, captions, summary of results), a schedule for the release, and a statement of the mechanisms for release. The intent is not to require concurrence for the release, but only to make sure that the Project Office, the Public Information Office, and NASA Headquarters are informed of the releases before they happen.

VI. MEP reserves the right to require a Principal Investigator to acquire and/or release immediately a limited set of data for purposes of public or educational outreach.

6.3 Data Release Acknowledgement Policy

In any release of data or information as described in sections 6.1 and 6.2 above, appropriate credit will be given to all entities involved, including the Principal Investigator, the Principal Investigator's home institution, JPL, and NASA. The credit will appear on public web sites that contain data releases and on documentation that accompanies the data products.

7 Documentation Concerning Returned Samples

Samples of rocks and soils may be returned from Mars as part of MEP. It is expected that the samples will be archived in an appropriate curatorial facility or facilities, where initial analyses will be conducted. This facility or facilities will also serve as a source of sample material for the science community.

It is crucial that observations that provide context (e.g., geological, geochemical, environmental) for returned samples also be archived. Such data must be archived in ways that can be easily linked to sample information developed by the curatorial facilities. To facilitate such links, it is expected that the PDS, MEP, and curatorial facility personnel will work together to establish data bases and procedures to connect mission and sample archives.

8 Archive Planning, Generation, Validation, and Delivery

Standard products form the core of the archives to be produced by MEP projects and released to the PDS for distribution to the science community. These products, SPICE files, software, and engineering and other ancillary information will be validated for transfer to the PDS.

The following section discusses the processes and schedules for generation and validation of standard products and archives by MEP projects. Figure 3 shows the flow of data through the stages of archives generation, validation, transfer to the Planetary Data System, and distribution to the science community. Also shown is posting of timely results on the Internet for education and outreach.

8.1 Archive Media

An *archive* consists of one or more data sets along with all the documentation and ancillary information needed to understand and use the data. Thus defined, an archive is a logical construct independent of the medium on which it is stored.

An *archive volume* is a unit of media on which an archive is stored; for example, one CD-ROM. When an archive spans multiple volumes, they are called an *archive volume set*. Usually the documentation and some ancillary files are repeated on each volume of the set, so that a single volume can be used alone.

Whole or partial archives may be placed online for convenient distribution via the Internet. However, to ensure long-term viability, archives must be also stored offline on physical archive volumes. The choice of storage medium will depend on available technology, but it should be a stable, industry-standard medium intended for long-term storage. At present, the standard media for long term storage are CD-ROMs and DVD-ROMs. Note that it is a requirement for each project to transfer to the PDS three copies of archives on hard digital media.

8.2 Planning and Documentation

Preparation for generating project data archives involves designing the data products, the online systems, and the physical archive volumes on which they will be stored, and developing the systematic generation, validation, and distribution procedures for these archive volumes. These plans will be documented in an Archive Volume Generation, Validation and Distribution Plan created by each project. These documents will cover all the standard data products generated by the project (e.g., Arvidson et al., 1997; Arvidson, 2001; Arvidson et al., 2002a; Arvidson et al., 2002b). For reference, Table 2 shows a suggested outline for an Archive Plan.

The format and content of data products are described in Data Product Software Interface Specification (SIS) documents, created by the instrument Principal Investigators or ancillary data product's cognizant engineer. Typically a separate SIS is created for each type of data product, including raw, derived and ancillary products. Table 4 is an example of a Data Product SIS outline, including annotations concerning the specific content recommended for each section. (Note that the example outline given is that of a completely self-contained Data Product SIS. If the pertinent information is available from other sources, e.g. data product labels and catalog descriptions, then sections of the Data Product SIS may simply refer the reader to those sources.)

The format and content of the archive volumes are described in an Archive Volume SIS for each data set, which is also generated by the Principal Investigator for the instrument or a cognizant engineer, working with relevant PDS personnel as needed. Table 5 is an example outline for an Archive Volume SIS. Table 6 shows a typical directory structure and contents for a PDS archive.

8.3 Generation

Generation of science data packets, EDRs, RDRs, and other data sets for a given MEP project is the responsibility of that project, as discussed in Section 4. Generation of archive volumes of raw (level 0) radio science data is the responsibility of the Radio Science Team associated with a given project or the project, as appropriate.

The DAWG or its equivalent for each project will provide oversight on implementation of the Archive Plan for that Project and ensure timely generation, validation, and delivery of archives to the PDS.

The MEP SDVT will provide overall oversight on archiving and operational processes for all MEP Projects, focusing on inter-project issues such as distributed operations infrastructures and related matters.

The Navigational and Ancillary Information Facility (NAIF) will generate an archive volume set of all SPICE data.

8.4 Validation and Delivery

Validation of engineering and science packets and SPICE files will be an intrinsic part of standard product generation. Further science validation of standard products will be done in part during analysis of the data.

A key additional requirement is the validation of archives for integrity of scientific content, file structures (e.g., do the files conform to Software Interface Specification documents?), directory structures, compliance with PDS standards, and integrity of the physical media used to transfer the data products. Validation will be coordinated through the DAWG or its equivalent and will follow the relevant Archive Plan. Interested members of the scientific community may also be asked to comment on plans for archive generation, validation, and delivery.

During the validation period, problems due to obvious errors in processing, missing files, and inadequate documentation will be referred back to the data suppliers for correction. Minor errors may simply be documented on the volumes. A fundamental aspect of the release schedule is that science packets, SPICE files, and algorithms/software generating derived data products are released at the same time as reduced data records generated from the relevant science packet data.

The DAWG will periodically report results of validation to the Project Science Group for the specific project. If the volumes are approved for release by the Project, then the Principal Investigator or relevant Project personnel would transfer the archives to the PDS, based on the release schedule specified by the Project's Archive Generation, Validation, and Distribution Plan. This may include online transfers and must include delivery of three copies of archives on hard digital media.

The PDS is responsible for delivering a copy of each archive volume set to the NSSDC.

9 Applicable Documents

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Planetary Data System Data Preparation Workbook, February 17, 1995, Version 3.1, JPL D-7669, Part-1.

Planetary Data System Standards Reference, July 24, 1995, Version 3.2. JPL D-7669, Part-2.

10 Definitions of Terms

Archive – An archive consists of one or more data sets along with all the documentation and ancillary information needed to understand and use the data. An archive is a logical construct independent of the medium on which it is stored.

Archive Volume, Archive Volume Set – A volume is a unit of media on which data products are stored; for example, one CD-ROM. An *archive volume* is a volume containing all or part of an archive; that is, data products plus documentation and ancillary files. When an archive spans multiple volumes, they are called an *archive volume set*. Usually the documentation and some ancillary files are repeated on each volume of the set, so that a single volume can be used alone.

Data Product – A labeled grouping of data resulting from a scientific observation, usually stored in one file. A product label identifies, describes, and defines the structure of the data. An example of a data product is a planetary image, a spectrum table, or a time series table.

Data Set – An accumulation of data products. A data set together with supporting documentation and ancillary files is an archive.

Experiment Data Records – NASA Level 0 data for a given instrument; raw data.

Reduced Data Records – Science data that have been processed from raw data to NASA Level 1 or higher. See Table 3 for definitions of processing levels.

Standard Data Product – A data product that has been defined during the proposal and selection process and that is contractually promised by the Principal Investigator as part of the investigation. Standard data products are generated in a predefined way, using well-understood procedures, and processed in "pipeline" fashion.

11 Tables

Table 1 – Instruments on Current MEP Projects and Expected Instruments on Upcoming Projects.

Note: Mars Pathfinder is a Discovery-class project. It is included because of relevance to MEP projects and objectives.

Project	**Instruments**
Mars Pathfinder	ASI/MET (Atmospheric Structure Instrument / Meteorology Package) IMP (Imager for Mars Pathfinder) MFEX (Microrover Flight Experiment (Sojourner Rover)) with APXS (Alpha Proton X-Ray Spectrometer)
Mars Global Surveyor	MAG/ER (Magnetometer/ Electron Reflectometer) MOC (Mars Orbiter Camera) MOLA (Mars Orbiter Laser Altimeter) TES (Thermal Emission Spectrometer) RS (Radio Science)
2001 Mars Odyssey Orbiter	THEMIS - Thermal-IR Multispectral Imaging System MARIE - Mars Radiation Environment Experiment GRS - Gamma Ray Spectrometer
2003 Mars Exploration Rovers	Twin rovers with Athena Payload: Pancam Navcam Mini-TES APXS Mössbauer Spectrometer Microscopic Imager Rock Abrasion Tool
2005 Mars Reconnaissance Orbiter	MARCI (Mars Color Imager)
	MCS (Mars Climate Sounder [formerly PMIRR])
	CTX (Mars Context Imager)
	CRISM (Compact Reconnaissance Imaging Spectrometer for Mars)
	HiRISE (High Resolution Imaging Science Experiment)
	SHARAD (Subsurface Sounding Shallow Radar)
	Gravity & Accelerometer Facility Science Investigations

Table 2 – Example Outline for Project Archive Generation, Validation and Distribution Plan

1. Introduction

   1.1 Purpose
   1.2 Scope
   1.3 Contents
   1.4 Applicable Documents and Constraints

2. Overview of Mission

3. Roles and Responsibilities

   3.1 Project
   3.2 Planetary Data System
   3.3 National Space Science Data Center

4. Archive Generation, Validation, Transfer, and Distribution

   4.1 Generation
   4.2 Validation
   4.3 Transfer
   4.4 Distribution

5. Archive Generation, Validation and Release Schedules

Table 1. Payload
Table 2. Definitions of Processing Levels for Science Data Sets
Table 3. Components of Archives
Table 4. Standard Data Products
Table 5. Archive Component Suppliers
Table 6. Archive Generation, Validation, and Release Schedule

Table 3 – NASA Definition of Processing Levels for Science Data Sets

NASA	**CODMAC**	**Description**
Packet data	Raw - Level 1	Telemetry data stream as received at the ground station, with science and engineering data embedded.
Level-0	Edited - Level 2	Instrument science data (e.g., raw voltages, counts) at full resolution, time ordered, with duplicates and transmission errors removed.
Level 1-A	Calibrated - Level 3	Level 0 data that have been located in space and may have been transformed (e.g., calibrated, rearranged) in a reversible manner and packaged with needed ancillary and auxiliary data (e.g., radiances with the calibration equations applied).
Level 1-B	Resampled - Level 4	Irreversibly transformed (e.g., resampled, remapped, calibrated) values of the instrument measurements (e.g., radiances, magnetic field strength).
Level 2	Derived - Level 5	Geophysical parameters, generally derived from Level 1 data, and located in space and time commensurate with instrument location, pointing, and sampling.
Level 3	Derived - Level 5	Geophysical parameters mapped onto uniform space-time grids.

Table 4 – Annotated Example Outline for Data Product SIS for Instrument-Related Data

1. Introduction

1.1. Purpose and Scope of Document

The purpose of this document is to provide users of the data product with a detailed description of the product and a description of how it was generated, including data sources and destinations. The document is intended to provide enough information to enable users to read and understand the data product. The users for whom this document is intended are the scientists who will analyze the data, including those associated with the project and those in the general planetary science community. This section should include a one-sentence description of the data product.

1.2 Contents

This data product SIS describes how the instrument acquires its data, and how the data are processed, formatted, labeled, and uniquely identified. The document discusses standards used in generating the product and software that may be used to access the product. The data product structure and organization is described in sufficient detail to enable a user to read the product. Finally, an example of a product label is provided.

1.3. Applicable Documents

PDS Standards and Data Dictionary documents

Science Data Management Plan for the project

Archive Generation, Validation and Distribution Plan for the project

Archive Volume SIS for the data product

Paper(s) describing the instrument

1.4. Relationships with Other Interfaces

State what products, software, and documents would be affected by a change in this data product. Refer to documents that describe the other interfaces.

2. Data Product Characteristics and Environment

2.1 Instrument Overview

Describe how the instrument acquires data; include a general description of operating modes as they relate to the data product.

2.2 Data Product Overview

Describe the type of data product (image, spectrum, etc.); what it measures (radiance, voltage, time, etc.); how observations are organized into data products; how a data product is stored (binary or ASCII, how grouped into files). Details should be specified in the following sections.

2.3 Data Processing

This section should provide general information about the data product content, format, size, and production rate. Details about data format should be specified later in section 6.

2.3.1 Data Processing Level

Describe the product in terms of its NASA and/or CODMAC processing levels.

2.3.2 Data Product Generation

Describe how and by whom data products are generated. Describe any calibrations, corrections, or compressions that have been applied to the product. Specify software, algorithms, calibration files or procedures. If a product has been compressed or otherwise processed in a reversible manner, indicate the software, algorithms, and/or ancillary data needed to reverse the processing, and describe how they should be applied. State whether multiple versions of the products will be generated.

2.3.3 Data Flow

Describe the sources, destinations, and transfer procedures for data products. State the size of an individual data product and the total size of all the data products generated over the course of each mission phase. State the time span covered by a product, if applicable, and the rate at which products are generated and delivered. If more than one version of a product may be generated, state the number of expected versions and the rate at which they will be generated.

2.3.4 Labeling and Identification

Indicate how an individual product is identified and labeled, including PDS labels and any other labels or header information. Details about label and header formats should be specified later in section 6. Each individual product should have a unique identifier; describe how this identifier is assigned. If multiple versions of a product are possible, state how they will be distinguished.

2.4. Standards Used in Generating Data Products

2.4.1 PDS Standards

State that the data products comply with Planetary Data System standards for file formats and labels. Refer to the PDS Standards Reference.

2.4.2 Time Standards

2.4.3 Coordinate Systems

2.4.4 Data Storage Conventions

Address any data storage issues, such as byte order, machine dependence, and compression.

2.5 Data Validation

Describe validation procedures applied to data products to ensure that their contents and format are free of errors. This may be a brief overview if the details are described in another document.

3. Detailed Data Product Specifications

Describe the physical organization of the data product so that the user can access and analyze the data.

3.1 Data Product Structure and Organization

3.2 Data Format Descriptions

3.3 Label and Header Descriptions

Include PDS labels and other labels and headers that describe the data.

4. Applicable Software

Describe any applicable software used to examine, display, or analyze the data products. State who produces the software and who uses it.

4.1 Utility Programs

Include image display tools, plotting tools, etc., that allow a user to examine the data.

4.2 Applicable PDS Software Tools

List the PDS software tools that may be useful in examining the data products.

4.3 Software Distribution and Update Procedures

Describe how the software is distributed and updated, and how the user can obtain it.

Appendices

A. **Glossary**

B. **Acronyms**

C. **Definitions of Data Processing Levels**

D. **Example PDS Label**

E. **Dictionary of PDS Label Keywords**

Table 5 – Example Outline for Archive Volume SIS for Instrument-Related Data

1 INTRODUCTION
- 1.1 Content Overview
- 1.2 Scope
- 1.3 Applicable Documents

2 INTERFACE CHARACTERISTICS
- 2.1 Operations Perspective
- 2.2 Volume and Size
- 2.3 Interface Medium Characteristics
- 2.4 Backup and Duplicate Copies

3 ARCHIVE FORMAT AND CONTENT
- 3.1 Format
  - 3.1.1 Disc Format
  - 3.1.2 File Formats
    - 3.1.2.1 Text Files
    - 3.1.2.2 Document Files
    - 3.1.2.3 Catalog Files
    - 3.1.2.4 Tabular Files
    - 3.1.2.5 PDS Label Files
    - 3.1.2.6 Data Files
- 3.2 Content
  - 3.2.1 Volume Set
  - 3.2.2 Directories
    - 3.2.2.1 Root Directory
    - 3.2.2.2 Calibration Subdirectory
    - 3.2.2.3 Catalog Subdirectory
    - 3.2.2.4 Document Subdirectory
    - 3.2.2.5 Gazetteer Subdirectory
    - 3.2.2.6 Geometry Subdirectory
    - 3.2.2.7 Index Subdirectory
    - 3.2.2.8 Label Subdirectory
    - 3.2.2.9 Software Subdirectory
    - 3.2.2.10 Data Subdirectories
    - 3.2.2.11 Extras Subdirectory

APPENDICES
- A. Mars Surveyor 2001 / Odyssey
- B. Mars Surveyor 2003 / Mars Exploration Rovers
- C. Mars Surveyor 2005 / Mars Reconnaissance Orbiter

Table 6 – Example of PDS Archive Volume Structure and Contents

The following is an example of the directory structure and contents of a typical PDS archive volume or volume set. Asterisks (*) indicate directories and files that are required for PDS archives. The archive may be stored on one or more physical volumes. In the event that multiple volumes are used to store a particular data set, typically all the directories are present on each volume in the volume set.

Directory	**Contents**
Root	*AAREADME.TXT: Introduction and general information for the user. ERRATA.TXT: Summary of anomalies found on this volume and on previous volumes in the set, if any. (Required file if there are comments or anomalies.) *VOLDESC.CAT: Description of the volume for the PDS Catalog.
*DOCUMENT	*DOCINFO.TXT: Description of files in the document directory. *VOLINFO.TXT: Overview of the mission, instruments, and the archiving process. Archive Volume SIS Data Product SISs Science Papers
CATALOG	CATINFO.TXT: Description of files in the catalog directory. CATALOG.CAT: Descriptions of mission, spacecraft, instrument and data sets for the PDS Catalog.
*INDEX	*INDXINFO.TXT: Description of files in the index directory. *INDEX.TAB: Table listing the data products on this volume and pertinent information about each one. *INDEX.LBL: PDS label describing the format of INDEX.TAB. CUMINDEX.TAB: Table listing the data products on this volume and all previous volumes in the set. CUMINDEX.LBL: PDS label describing the format of CUMINDEX.TAB.
LABEL	LABINFO.TXT: Description of files in the label directory. Additional PDS labels and include files that are not packaged with the data products.
SOFTWARE	SOFTINFO.TXT: Description of files in the software directory Software programs, utilities, or libraries used to access and/or process the data products Source code and/or algorithms Build instructions for various platforms
CALIB	CALINFO.TXT: Description of files in the calib directory Calibration files used to create the data products or needed for processing the data products.
GEOMETRY	GEOMINFO.TXT: Description of files in the geometry directory SPICE and other files needed to describe the observation geometry.
*DATA	Data products with PDS labels. A data product's label may be attached (embedded at the beginning of the file) or detached (stored in a separate file in the same directory). Typically the DATA directory is divided into subdirectories so that no more than about 100 files are present in one directory.

12 Figures

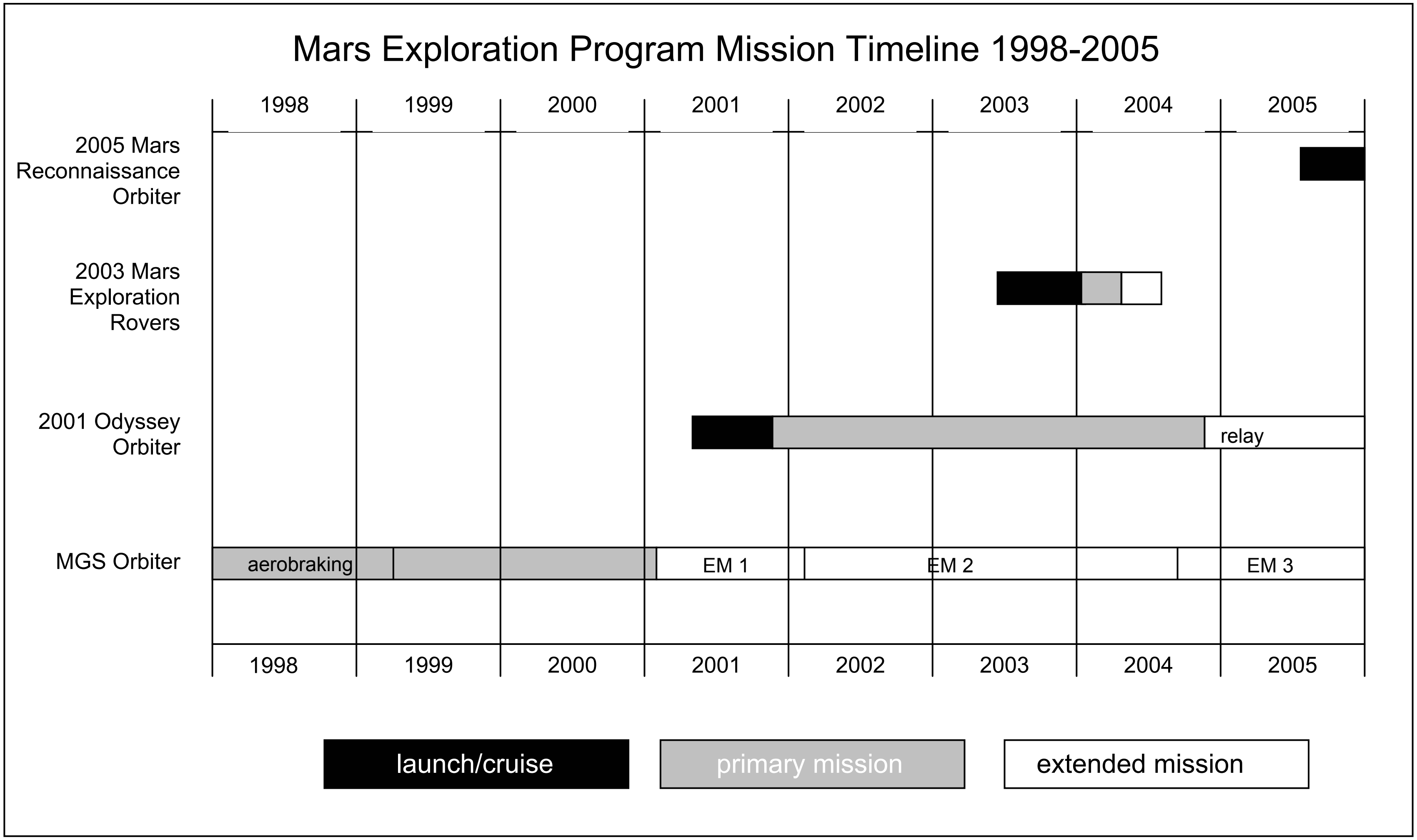

Figure 1 – Timeline for Exploration Program Projects.

Calendar years are shown.

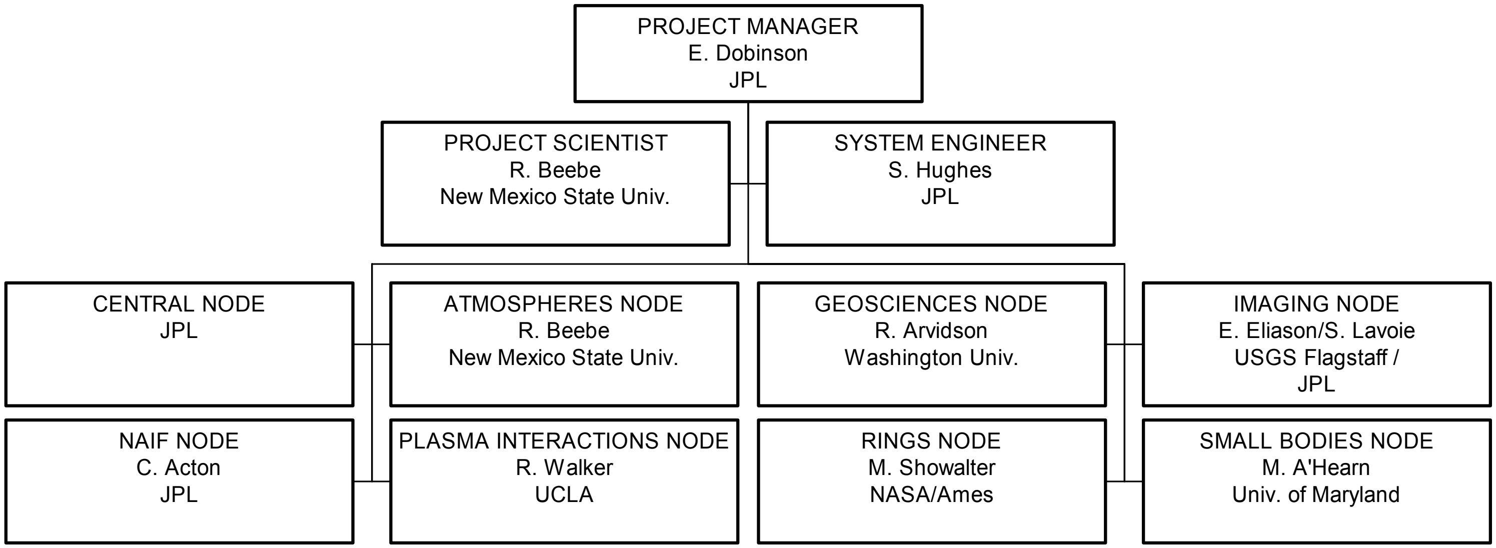

Figure 2 – Planetary Data System Organizational Structure.

Not shown are the extensive set of geographically distributed subnodes and data nodes, and the Radio Science support node at Stanford University led by R. Simpson.

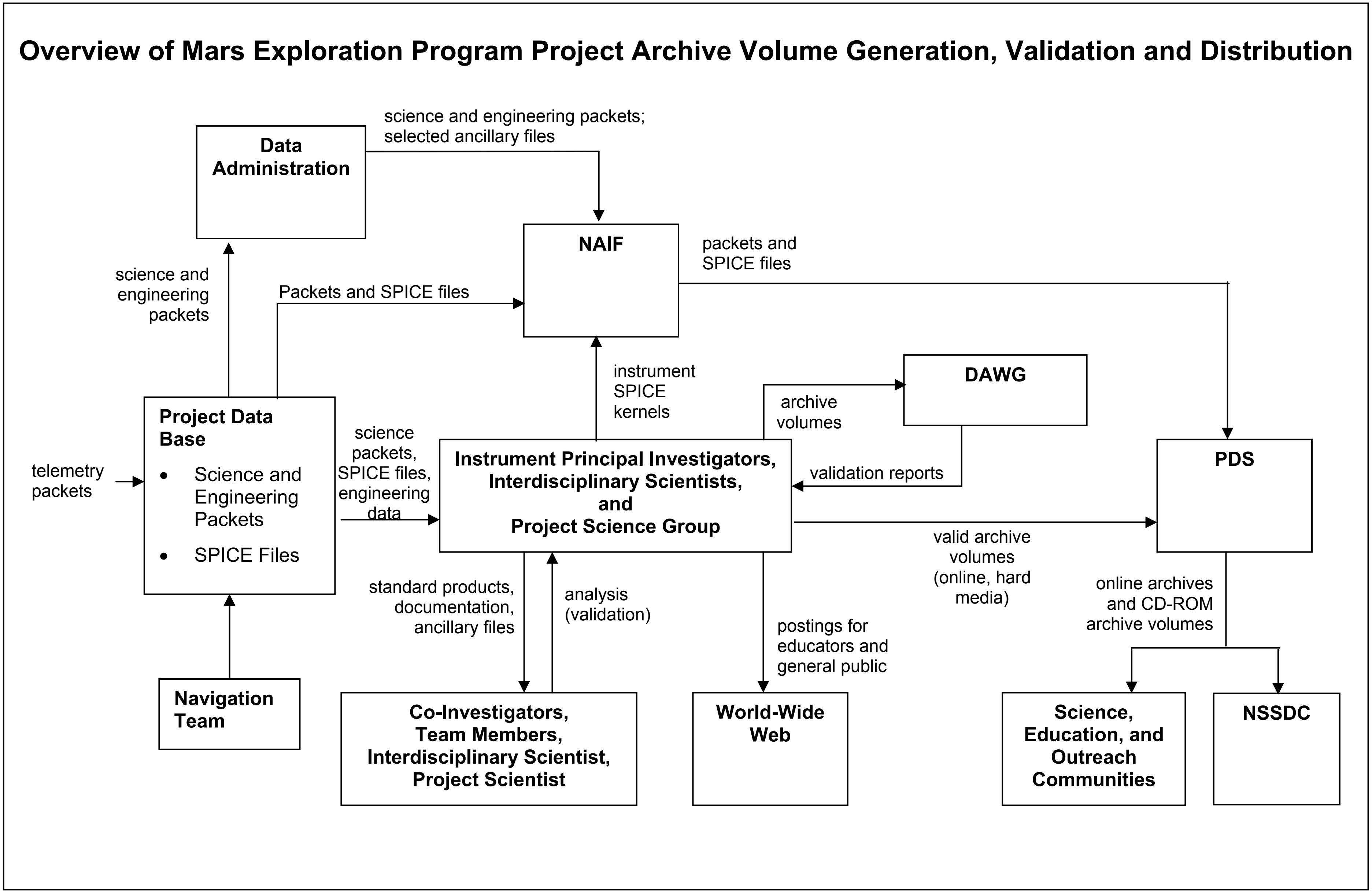

Figure 3 – Flow of Archive Volume Generation, Validation and Distribution Functions for Mars Exploration Program Projects