The Preparation for and Execution of Engineering Operations for the Mars Curiosity Rover Mission

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Abstract - *The Mars Science Laboratory Curiosity Rover mission is the most complex and scientifically packed rover that has ever been operated on the surface of Mars. The preparation leading up to the surface mission involved various tests, contingency planning and integration of plans between various teams and scientists for determining how operation of the spacecraft (s/c) would be facilitated. In addition, a focused set of initial set of health checks needed to be defined and created in order to ensure successful operation of rover subsystems before embarking on a two year science journey. This paper will define the role and responsibilities of the Engineering Operations team, the process involved in preparing the team for rover surface operations, the predefined engineering activities performed during the early portion of the mission, and the evaluation process used for initial and day to day spacecraft operational assessment.*

Keywords: Mars, Rover, Operations, Engineering activities.

1 Mission and Rover Design Summary

The Mars Science Laboratory Mission's rover, named *Curiosity* was launched from Kennedy Space Center on November 26th, 2011 and successfully landed at Gale Crater, Mars on August 5th, 2012. The rover was designed for a Prime Mission of one Martian year (669 Martian days, called sols) which equates to just under two Earth years. The 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. [1]

The Curiosity rover is approximately 900kg and equipped with ten different science instruments, contributed by eight different instrument teams. Five of these instruments have non-United States based teams spanning across various time zones across the globe. The rover was designed to perform environmental, remote, contact, and analytical science. With a five degree of freedom, 2m long robotic arm, *Curiosity* is capable of placing different science instruments or tools on the Martian soil, or acquiring soil samples by either scooping or using its percussive drill to core samples up to 5cm in depth. Additionally, the rover is capable of traversing up to 1km using its six wheel drive, four wheel steering, rocker-bogie mobility system. The rover has approximately a 2.2m wheel base, deck height of 1.1m, and maximum height of 2.2m at the top of the Remote Sensing Mast. See Figure 1 below for a summary of Curiosity's science instrument payload suite and an overview of the key rover subsystems. Additional information regarding the spacecraft (s/c) design and instrument capabilities may be found on NASA's Curiosity Rover website [2].

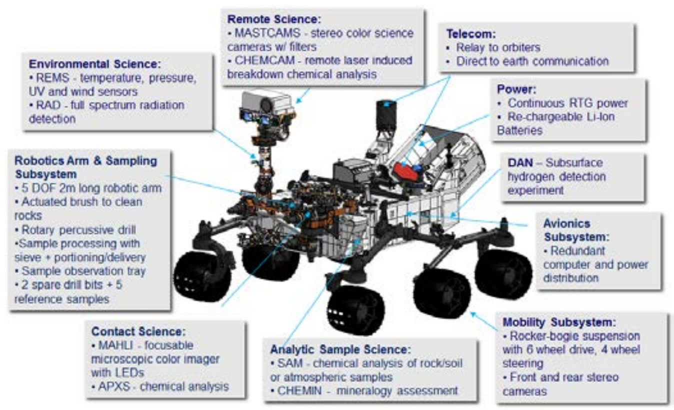

Figure 1. Curiosity Rover Overview

Operationally, a sol (a Martian day), is typically categorized into a specific sol type, such as Traverse, Reconnaissance, Approach, Contact, Sampling or Analysis depending on the type of activities intended to be performed. Each of these sol types has their own baseline estimate for power consumption, data volume generation, and execution duration. The primary awake period of the rover is from 10:00 local Mars solar time (LMST) to 16:00LMST when there is light available for camera operation and the mechanisms and camera hardware are warm. The rover has a finite amount of energy available for each sol and activity plans must fit within this available amount. Sol plans therefore need to be sure to provide a sufficient amount of sleep time where the Li-Ion batteries can be recharged. Operations are not completely constrained to this time of day range. The operations team may choose to wake up the vehicle early to perform early morning science blocks, as well as wake up during various points during the night to turn on or read out data from instruments which are capable of operating while the rest of the rover is asleep. The rover is commanded the morning of each sol typically via a direct from Earth (DFE) x-band radio communication session where the entire set of instructions are issued (radiated) in the form of command sequence files. The primary method of transferring spacecraft data, or telemetry to the ground operations team is via a relay link first to the Mars Reconnaissance Orbiter (MRO) or the Mars Odyssey (ODY) spacecraft, where then they transmit the data back to Earth. These relay opportunities occur during the afternoon and early morning of each sol, aligned with the relay spacecraft's orbit. The operations team uses the relay data from the afternoon in order to plan the next sol's activities. This data set is considered the "decisional" data and contains the critical telemetry required to assess the vehicle's safety, execution and performance of the commanded sequences, and provides the information required by the team for the perform the planning of the subsequent sol's activities. This process is the foundation of the tactical operations uplink and downlink cycle.

2 Operations Concept Overview

The baseline tactical operations plan was that the operations team would operate on Mars-time, seven days a week through first 90 sols. This means, the downlink assessment of the decisional data would occur immediately when that data became available. This data could arrive at any time of day on Earth depending on the Earth-Mars sol time alignment. Note that a Martian sol is 1.027 times longer than an Earth day. Because of the additional minutes in a sol, the time on Earth will advance each day by ~39min in order stay synchronized with the time on Mars. This concept is called Mars-time. All members of the project operations team, including the scientists, were co-located and operating on Mars-time at the Jet Propulsion Laboratory in Pasadena during this period. After the first 90 sols, the team migrated to "Earth-time" operations where the work day became bounded from as early as 6:00PST to 23:00PST. This was performed seven days a week up to 180 sols, and then transition to five days a week, Earth-time operations through the end of the mission.

The execution duration of the overall tactical timeline at the time of spacecraft landing was 16 hours and has since reduced down to 10 hours. The tactical operations process is the operations team responding to the sol n-1 downlink to generate and implement a command load for uplink on the morning of sol n. See Figure 2 below for the key steps in the tactical operations flow. The ground activity planning and commanding portion of the sol comprises the majority of the tactical operations timeline. During this period, plans are negotiated amongst the science teams, refined, assembled and validated.

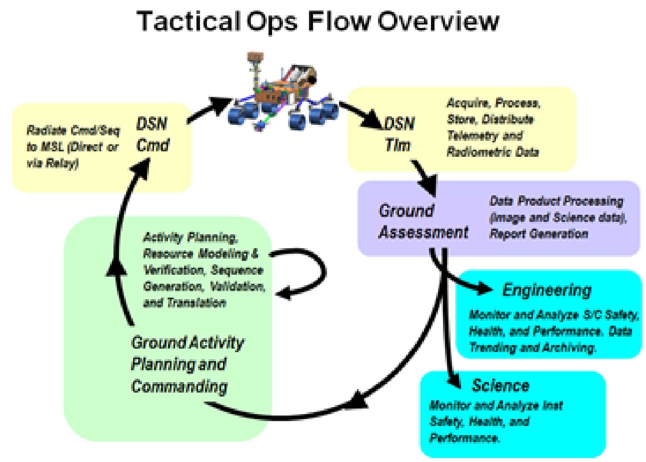

Figure 2. Tactical Operations Flow

Additionally, there is a supra-tactical process that must stay in lock-step with the tactical process. This process preforms the pre-planning for subsequent sols based on the current tactical operations activity flow. The process is similar to that for tactical process and requires products to be delivered every sol for tactical ingestion (e.g., look-ahead plan is input to sol n+1 skeleton update).

There are also many activities however, that need more time than the tactical timeline allows in order to develop and validate. These activities are developed on the strategic timeline process. Examples of these activities would be the generation of the sample handoff sequences and scripts, certain engineering activities like a flight software version updates, or new capabilities to be exercised on the rover for the first time.

The Mars Science Laboratory's surface tactical, supra-tactical and strategic mission operational processes are accomplished by multiple teams. They are as follows:

- Real Time Operations (RTO) Team: Provides support for spacecraft commanding and telemetry processing.
- Engineering Operations (EO) Team: Responsible for the analysis of the spacecraft activity performance, health of the vehicle and targeted engineering or spacecraft maintenance activities.
- Science Office (SO): Defines and guides the mission activities and daily sol plans based on scientific goals of the mission.
- Integration Planning and Execution (IPE) Team: Generates the spacecraft uplink products and is responsible the construction of an implementable tactical activity plan and corresponding products to be executed on the spacecraft.

2.1 Engineering Operations Team Roles and Responsibilities

During the operations preparation period prior to landing, the Engineering Operations team was responsible for generating the tools, procedures and processes for verifying the spacecraft operation, and providing the state input and constraint limitations to be used as part of the tactical planning process. Specifically, the EO team was responsible for generating, delivering, and validating the power and thermal models used for daily planning of rover operations. Additionally, the EO team also generated and validated the tools used to assess and predict other spacecraft and operational performance values such as telecom data rates/volumes, high gain antenna (HGA) pointing error, spacecraft attitude estimation, power consumption and availability, spacecraft hardware and environmental temperature ranges, and on board data file management.

In addition to creating the procedures and tools (automated analysis scripts) for spacecraft data downlink assessment, the team also examined and developed rover contingency operations processes, and diagnostic and recovery procedures. Some of the pre-defined contingency or spacecraft recovery activities that the team prepared for prior to landing were:

- Loss of X-band or UHF Communication
- Device hardware swap from primary to backup unit
- Flight Software anomalous behavior
- Thermal behavior or device failure
- Recovery of the spacecraft from Safe Mode

Since the Engineering Operations team is also responsible for execution of the core engineering functions of the rover and any required maintenance activities, prior to landing the team developed the model for the development and delivery of certain engineering sequences and the process for how to integrate these activities in the nominal tactical sol planning process. The data management process for example needed to be able to provide the expected data volume available for use by the science team for a given sol. This volume is a function of relay over flight geometry and link bandwidth, the number of products already on board the spacecraft which are candidates for transmission, and the downlink prioritization scheme for products which are intended to be created. This information needed to be generated and integrated into the tactical planning tool MSLICE in order for the team to guarantee receipt of the sol's critical data. Similar MSLICE interfaces were developed for evaluation and communication of required mechanism actuator or camera warmup heating and its associated energy impacts.

As part of tactical operations post landing, the EO team is responsible for performing the rover spacecraft health and activity performance assessment on a tactical sol by sol basis. The EO downlink assessment team, via the Tactical Downlink Lead Engineer provides input to the uplink planning process regarding state of vehicle and its ability to perform the next sols activity plan. Each sol, the EO team also provides uplink products (in the form of flight sequences and files) to support spacecraft maintenance or diagnostic activities, device warmup heating, data product and/or communication window management, and any other engineering related vehicle functions.

The Engineering Operations team is comprised of various roles. They all have a dedicated seat in the Mission Support Area at JPL. See Figure 3 for a layout of the Surface Mission Support Area (SMSA) and the configuration of the support roles.

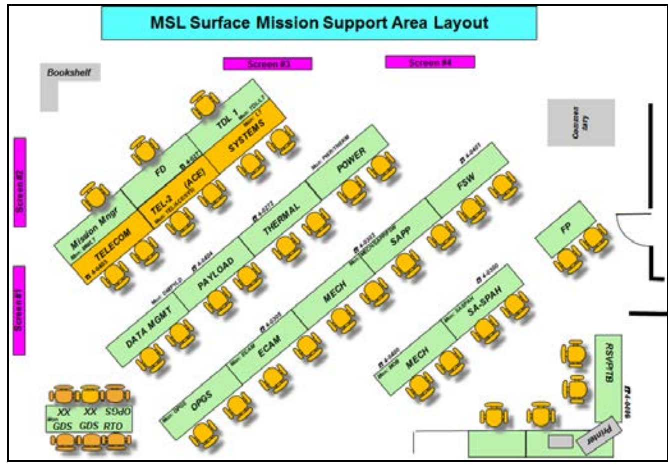

Figure 3. Surface Mission Support Area, JPL

Each of the roles has their individual contribution to the assessment and intended manner of operating the spacecraft, but it is the collective assessment across all the areas that provided the evaluation of the overall health and state of the rover. The responsibilities of the individual EO ops team roles are as follows:

<u>Flight Director (FD):</u> Staffed only during the early portion of the mission during the Characterization Activity Phase. This person leads and organizes downlink assessment by the engineering team (team polls, reviews and certifies the command load transmitted to the spacecraft, directs the team in anomaly response activities, and assures timely resolution of issues.

<u>Tactical Downlink Lead (TDL):</u> Also leads the engineering operations team in the assessment of vehicle health and safety status at each critical downlink, assures timely resolution of all anomalies, identifies constraints on subsequent rover planned activities based on the received spacecraft data, provides engineering sequences that maintain calibration and operational readiness of vehicle components and participate in the reviews conducted during the sequence plan development process.

<u>Tactical Systems Engineer (TSE):</u> Supports tactical downlink assessment; provides assessment on activity and sequence completion status, evaluates any warnings or faults, checks the state of various counters/timers and reviews subsystem trend data. The Tactical Systems engineer also keeps the record of running s/c issues and constraints, and supports the TDL/FD with anomaly

investigation/debug activities as required. The TSE also maintains the record of long term strategic engineering maintenance activities and works with Strategic Systems and the TDL/EUL to develop and incorporate these activities into the tactical process.

Strategic Systems Engineer (SSE): Supports the development and testing of first time activities and any ops product verification and validation outside of the tactical timeline. The SSE provides input and support to the tactical systems team for incorporation of strategically built activities into the tactical plan as well as is available to work anomaly investigations.

Engineering Uplink Lead (EUL): Supports the sequence preparation and validation portion of the tactical timeline. The EUL is responsible for engineering sequences for device warmup, communication window changes, engineering maintenance activities, calibrations, and other EO subsystem provided requests. The EUL supports the final review and certification of the command load transmitted to the spacecraft. The EUL also generates the radiation instruction log which is used to issue the final products to the spacecraft over the Deep Space Network (DSN).

Power Engineer: The power engineer assesses the performance of the battery and radio-isotope thermoelectric generator (RTG) power hardware on each downlink and compares the performance against the predicted performance. Additionally, the power engineer monitors the device power state of all components and may recommend adjustments in any component modeled settings, or request any additional acquisition of data or changes in operational behavior to ensure positive power system performance. Once the downlink assessment has been completed, the power team delivers an initial condition state files which is then used as a starting point for subsequent sol plan development.

Thermal Engineer: Assesses the thermal performance of the thermal device hardware (PRTs, heaters) as well as the actively controlled, pump driven, heat rejection system. Additionally, the thermal engineer checks component temperatures on each downlink, compares performance against predicts, and recommends adjustments in any heater setpoints or warm up durations in order to maintain components within their allowable flight temperature operating range. The thermal team is responsible for generating seasonal temperature predicts and energy estimation for device survival heating.

Data Management (DMX) Engineer: Performs the analysis of what products were transmitted for a given downlink pass, the downlink processing and data file management performance, and the assessment of what may need to be retransmitted due to gaps in the transmission. The DMX engineer is responsible for maintenance of all data products in memory and generates any delete, retransmission or reprioritization commands based on ops team input.

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Fault Protection Engineer: Evaluates any fault occurrences on the spacecraft and provides recommendation on analyses or recovery responses to resolve the problem.

Telecom Engineer: Assesses the performance of the telecommunication hardware on the spacecraft and recommends any adjustments in configuration to resolve, maintain or achieve downlink or uplink capabilities. The telecom team prepares data volume and radio performance predictions as well as reviews all communication window configuration products prior to upload to the spacecraft.

Surface Attitude Pointing and Positioning (SAPP): Reports the state of the spacecraft attitude and state of health of all attitude sensors. Provides predicts of both pointing constraints and possible equipment obstruction in the pointing of the HGA, based on vehicle attitude.

Mechanisms Engineer: Evaluates the performance of all the spacecraft actuators and reports on the state and operational performance of the High Gain Antenna (HGA) and Remote Sensing Mast (RSM) mechanisms. This role also provides the rover kinematic state initial conditions file for the uplink planning process that the vehicle physical configuration is adequately captured at the beginning of the planning process.

Sample Acquisition and Sample Processing and Handling (SA/SPaH): Assesses the performance of the robotic arm, drill, scoop, dust removal tool, CHIMRA sample processing hardware and inlet covers. Reports on the overall performance of contact, sampling and instrument sample drop off related activities and provides input and guidance for sample acquisition and processing plans to the uplink planning and commanding process.

Mobility Engineer: Evaluates the performance of driving operations and the state of the mobility hardware. This includes the assessment of actual versus planned drive elements, estimation of final position, terrain assessment evaluation that assists in explaining actual performance of the drive system, and rover slip assessment during command drive motions, or while static. The mobility team also assists the rover planners in the preparation of subsequent drives.

3 Preparation for Operations

3.1 Requirement Verification and Validation

Similar to the Verification and Validation process of the spacecraft [3] the mission operations system used a similar process for the verification and validation of its requirements. Specifically, Operation Readiness Tests (ORTs) and Thread Tests (TT) were used to examine, exercise, and certify the capabilities and preparedness of the Operations team personnel and the associated tools needed to perform the tactical process. These tests involved all MSL Surface teams (and the Entry Descent and Landing team as appropriate) as well as interfacing ops teams such as the Data Support Operations Team and Deep Space Network (DSOT/DSN) and UHF relay partners MRO & ODY.

The following Thread and Operational Readiness Tests were performed as part of the operations V&V program. Each test had primary and secondary objective for each of the different operations teams and was performed in the operations environment primarily using the System Testbed test environment as the representation of the spacecraft. ORTs typically were performed with the full operations team on a representative Mars time tactical timeline, where TTs may have only focused on a subset of functions, tools, or team members.

- Characterization Activity Phase (CAP1a) Thread Test, 8/22-8/26 (2011): Initial exercise of Sols 0 to 4 and the Characterization Activity Phase (CAP) ops concept.
- Surface Nominal Thread Test (SNTT), 10/23 – 10/28 (2011): First demonstration of nominal ops process for a recon, approach, contact, and sample analysis sol.
- Characterization Activity Phase (CAP2) Thread Test, 12/11-12/15 (2011): Initial exercise of the surface sampling and science hardware checkout activities.
- Sample Analysis Thread Test (SATT), 1/24 – 1/27 (2012): Successfully exercised key aspects of the end-to-end drilling, sample processing and analysis in order to check out the ops concept and early version of tools.
- ORT7B, 2/27 – 3/8 (2012): Exercised CAP operations on the flight like tactical timeline. Exercised all key CAP activities such as deployments, checkouts of all instruments and mechanisms, executed the FSW transition from the Cruise/EDL load to the surface FSW load, and performed opportunistic science. This test also exercised UHF relay ops with MRO & ODY test platforms.
- ORT8, 4/17 – 4/22 (2012): Exercised five sols of tactical uplink/downlink process cycles for nominal science ops.; recon, approach, contact and sampling & analysis. This test also exercised initial version of the supra-tactical operations process along with the strategic UHF forward link process.
- ORT 11, 5/17 – 5/22 (2012): Exercised off nominal Sol 0 to Sol 4 (CAP 1a plus FSW transition). Demonstrated the ops team's ability to detect and diagnose spacecraft anomalies, recover the spacecraft to a safe state, and initiate actions to return back to nominal ops. This test also demonstrated the operational transition between the cruise/EDL and surface phases of the mission and the handoff between teams, tools and processes. The DSN and orbiter team interactions were also tested in a flight-like way.
- CAP V&V Thread Test, 6/11-6/15 (2012): Successfully tested near-final flight products for CAP 1a, the flight-like downlink assessments of go/no-go criteria for rover hardware deployments and state changes.
- FSW Transition TT (6/14-15/12, 7/15-17/12): Successfully exercised the final flight products for the FSW transition to R10.5, flight-like downlink assessments of go/no-go criteria evaluation for transition decisions using the final activity on-console procedures.
- End to End Surface Sampling TT 6/21-22 (2012): Successfully exercised end-to-end sample acquisition, delivery and analysis and the associated gate decision process steps, product generation and downlink analysis.
- UHF Relay TT, 6/18 & 6/25 (2012): Performed tactical communication changes into the Mars Relay Operations Service (MAROS) tool, demonstrating coordination across relay teams and propagation to ops pass information tools. Successfully exercised the flight-like planning process with the MRO, ODY and Lockheed Martin teams.
- Tactical Activity Planning and Sequencing Thread (TAPST) 6/19-6/20, (2012): Successfully exercised the nominal tactical uplink process and tools in flight-like way for final pre-landing validation.
- Data Management TT (7/3/12): Final validation of data management process including science team interactions, with the landing version of the Data Management Toolkit Tool (DMTK).
- ORT14 (7/10/12-7/14/12) : Final exercise of the EDL to Surface transition, initial CAP activities and go/no-go criteria evaluation.

3.2 Operational Flow Development

The choreography of the tactical operations process was a collaborative effort across all of the operations teams (IPE, EO, SO & RTO). While the initial model for MSL operations was based on the Mars Exploration Rover Mission model, the details behind the interfaces, tools and unique characteristics and challenges of a Mars sampling mission with a significantly more complex rover design and instrument suite, provided for creative and alternative solutions. The method that the teams chose to capture these operational agreements and interfaces was via Operational Interface Agreement (OIA) documents. The Engineering Operations team alone developed 32 of these OIAs capturing the expectation of certain input/output files, the timing of product deliveries, and the overall definition of information that is relayed as part of the tactical operations process. For specific products which were passed back and forth across teams, 19 corresponding Software Interface Specifications were written to record the file formats in order to prevent downstream tool or script processing issues.

4 Execution of Early Operations

4.1 Characterization Activity Phase

The MSL project decided prior to landing that the first month or so of the mission would be dedicated to a Characterization Activity Phase. During this period, pre-defined and pre-tested activities would be executed in order to check-out the overall rover health prior to enabling nominal surface operations. Objectives during this period included initial deployment of launch/cruise configured hardware, the robotic arm and initial motion of the mobility system. It also established and characterized all communications links, exercised the payload instruments and transitioned from the cruise/EDL software version to the surface software version. Additionally, critical surface sampling hardware was exercised in preparation for future contact science and sampling.

The model for the overall characterization phase was such that it would be broken up into the following sections noted below. Execution of these activities adhered within 1 day of the predicted plan.

- CAP1a: Pyro Firing, R9 FSW parameter setting, Deployment of HGA and RSM, all instrument aliveness checks, initial imaging, power/thermal subsystem characterization, establishment of UHF / HGA Communication, return EDL data.
- CAP1b: Transition to FSW R10.5.6, configure R10 parameters, perform instrument health checks on new FSW, upgrade motor control FSW version, perform mobility checkout & bump, and unstow/stow of the robotic arm.
- Perform nominal Science once an instrument has been checked out except in the cases where the instrument activity was a First Time Activity in which case a separate preparation and readiness evaluation process was used.
- CAP2a: Robotic Arm Deploy & Contact Science Characterization
- Intermission: Mastcam Characterization, Chemcam characterization, SAM instrument plumbing / atmospheric checkout, blind drive, and DAN instrument spatial profile
- CAP2b: Prepare for First Sample Acquisition, Processing, and Delivery.

Following the Characterization Activity Phase, the operations team progressed with nominal tactical spacecraft operations.

4.2 Spacecraft Health Assessment Process

The Engineering Operations team's model for downlink assessment was such that specific Characterization Activity Phase downlink assessment procedures would be written, in addition to the nominal downlink assessment procedures. Along with the general health evaluation of the rover, the CAP specific procedures called out the specific success criteria for the Go/No-Go activity evaluation needed in order to proceed with subsequent CAP activities. Additionally, the surface operations team began tactically supporting operations the full week prior to landing. Representatives from key areas (Systems, Power, Thermal, Data Management) would provide their own independent evaluation of the spacecraft in relation to upcoming surface operations. Immediately after touchdown, the control and responsibility of the spacecraft transferred from the Cruise/EDL Mission Support Area (CMSA) to the Surface Mission Support Area (SMSA) and the entire surface operations team.

5 Summary

The execution of surface operations is a collaborative process spanning across many teams. The use of flight like operational tests, interface documentation and a clear set of roles, responsibilities, and initial pre-scripted mission activities paved the way to a very successful start of MSL surface operations.

Acknowledgement

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