Human Mars Surface Science Operations

Marianne R. Bobskill[1]
NASA Langley Research Center, Hampton, VA 23681

and

Mark L. Lupisella[2]
NASA Goddard Spaceflight Center, Greenbelt, MD

Human missions to the surface of Mars will have challenging science operations. This paper will explore some of those challenges, based on science operations considerations as part of more general operational concepts being developed by NASA's Human Spaceflight Architecture (HAT) Mars Destination Operations Team (DOT). The HAT Mars DOT has been developing comprehensive surface operations concepts with an initial emphasis on a multi-phased mission that includes a 500-day surface stay. This paper will address crew science activities, operational details and potential architectural and system implications in the areas of (a) traverse planning and execution, (b) sample acquisition and sample handling, (c) *in-situ* science analysis, and (d) planetary protection. Three cross-cutting themes will also be explored in this paper: (a) contamination control, (b) low-latency telerobotic science, and (c) crew autonomy. The present traverses under consideration are based on the report, *Planning for the Scientific Exploration of Mars by Humans*[1], by the Mars Exploration Planning and Analysis Group (MEPAG) Human Exploration of Mars-Science Analysis Group (HEM-SAG). The traverses are ambitious and the role of science in those traverses is a key component that will be discussed in this paper.

The process of obtaining, handling, and analyzing samples will be an important part of ensuring acceptable science return. Meeting planetary protection protocols will be a key challenge and this paper will explore operational strategies and system designs to meet the challenges of planetary protection, particularly with respect to the exploration of "special regions." A significant challenge for Mars surface science operations with crew is preserving science sample integrity in what will likely be an uncertain environment. Crewed mission surface assets -- such as habitats, spacesuits, and pressurized rovers -- could be a significant source of contamination due to venting, out-gassing and cleanliness levels associated with crew presence. Low-latency telerobotic science operations has the potential to address a number of contamination control and planetary protection issues and will be explored in this paper. Crew autonomy is another key cross-cutting challenge regarding Mars surface science operations, because the communications delay between earth and Mars could as high as 20 minutes one way, likely requiring the crew to perform many science tasks without direct timely intervention from ground support on earth. Striking the operational balance between crew autonomy and earth support will be a key challenge that this paper will address.

---

[1] Senior Space Systems Analyst, Space Missions Analysis Branch, Systems Analysis & Concepts Directorate, 1 North Dryden Street, Hampton, VA / Mail Stop 462, AIAA Non-Member.
[2] Systems Engineer, Exploration Systems Projects, Flight Projects Directorate, 8800 Greenbelt Rd., Greenbelt, MD / Mail Stop 581, AIAA Non-Member.

I. Introduction

Human missions to the surface of Mars, particularly long duration missions, will present novel and challenging science operations. This paper will explore some of those challenges based on science operations considerations as part of more general operational concepts being developed by NASA's Human Spaceflight Architecture (HAT) Mars Destination Operations Team (DOT). The HAT Mars DOT has been developing comprehensive surface operations concepts with an initial emphasis on a multi-phased mission that includes a 500-day surface stay, and a more detailed description of that work is being prepared by the full study team as a NASA report. This paper will address crew science activities, operational details and potential architectural and system implications in the areas of (a) traverse planning, (b) sample acquisition and sample handling, (c) *in-situ* science analysis, (d) drilling (both shallow regolith and deep drilling), (e) planetary protection, and (f) human research. Three cross-cutting themes that will also be explored in this paper are: (a) contamination control, (b) low-latency telerobotic science, and (c) crew autonomy.

The primary objective of the HAT Mars DOT was to assess Mars surface strategies for human exploration in sufficient depth to capture the range of capabilities needed to inform architectures, system design, and technology investments and to better understand and inform linkages across NASA's Science and Human Exploration and Operations Mission Directorates, including strategic knowledge gaps that have been developed to reduce risk for eventual human missions to Mars. The NASA Mars Design Reference Architecture (DRA 5.0, *NASA Human Exploration of Mars* + Addendum[2]) was used as the key mission context and was re-examined in light of long-duration human Mars surface operations. Early in the study, a "functional decomposition and capability audit" of the DRA 5.0 surface mission was performed and the team developed a "Point of Departure" (POD) Surface Concept of Operations ("ConOps"). A representative surface mission system manifest and mass estimates were developed and compared to the envisioned required capabilities and mass estimates of the DRA 5.0 baseline.

A number of special studies were conducted by the broader team. This paper includes results from the Mars Laboratory and Sampling Handling Study and some results from other areas, such as traverse planning and integrated drilling. Additional results from the other studies are not presented in this paper, but will be included in the full NASA report. The following focused analyses were performed as part of this overall human Mars surface mission study:

- Mars Laboratory and Sample Handling
- Functionality & Capabilities Assessment
- Commodity Cache Feasibility
- Traverse Planning and Mobility
- Integrated Surface Power
- Integrated Drilling Strategy
- Statistical Modeling

II. Science Information as the Foudation for Concept of Operations Development

An approach was defined to collect and organize science information to serve as the foundation for development of crew science operations within the developing POD ConOPs for a crewed Mars long-stay surface mission. This information collection approach involved a number of tasks and was carried out by DOT members prior to beginning development of the ConOps. This science information collection approach is summarized in this section with representative examples of the information derived that was used during ConOps development.

First, two primary reference sources were identified and reviewed in detail. The first reference, the MEPAG HEM-SAG document, *Planning for the Scientific Exploration of Mars by Humans*[1], served as one of the two foundational documents for Mars ConOps development. It was reviewed and a detailed summary was created to serve as a working reference during ConOps development. The MEPAG HEM-SAG document contained information regarding:

- Mars science goals & objectives across geology, geophysics, atmospheric & climate science, and astrobiology disciplines
- Specific science questions to be addressed within each science discipline
- Types of crew and robotic activities that should be conducted

- Supporting capabilities to enable these crew and robotic activities

This information was used as primary input into the Mars surface mission ConOps (in particular, the proposed Mars surface traverses). The second primary reference source was the set of documents associated with NASA's Mars DRA 5.0: *The Mars Surface Reference Mission*[2].

DOT also hosted a series of special briefings, where the team was briefed by Subject Matter Experts (SMEs) across three domains related to Mars surface operations. A briefing describing "Deep Drilling on Earth and Mars" was given by Mr. Roy Long, Ultra-Deepwater Technology Manager at the US Department of Energy's National Energy Technology Laboratory. A briefing focused on "Biocontainment of Earth and Mars Pathogens" was given by Dr. Katharine Rubins, a member of NASA's Astronaut Office and a specialist in Molecular & Cancer Biology. And a final SME briefing was given by Dr. Catharine A. Conley, NASA's Planetary Protection Officer, based at NASA Headquarters, describing Planetary Protection issues and protocols associated with Mars operations.

In addition, the DOT created a "workbook" to provide a mechanism by which science discipline SMEs from the MEPAG HEM-SAG team could provide answers to a set of questions regarding Mars surface operations within their discipline. The science disciplines for which detailed information was gathered from the SMEs included Mars (1) geology, (2) geophysics, (3) atmosphere & climate science, and (4) astrobiology. The workbook questions related to Mars surface operations driven by science objectives and surface activities; information was gathered from the SMEs regarding the following questions and associated issues:

- Sampling location: fixed site, many sites
- Drilling depth (in meters)
- Landing site proximity: local (<10 km), regional (>10 km)
- Data collection approach: stationary, during traverse
- Data collection resources: passive, active
- Data analysis location: in-situ surface, in-situ subsurface, surface lab, earth lab
- Data/sample return: data returned, sample returned (in sealed container), sample returned (requires special environment)
- During mission phase (1 through 6): robot only, crew + robot, crew only
- Contamination control requirements related to the obtained sample
- Data rate/frequency
- Are precursor measurements required?
- Operational notes/recommendations

Upon completion of the workbook by the SMEs, a telecon was held with the SME for each science discipline where the DOT and science discipline SME's reviewed the information and questions were addressed. These interviews were then transcribed and used as a primary reference during Mars surface mission ConOps development.

The DOT held an "Educational Forum," during which SMEs in five fields were asked to brief the team on broad topics of importance to the Mars surface mission ConOps in development. The areas briefed by SMEs to the DOT were:

- Mars surface Extravehicular Activity (EVA)
- Crew medical issues regarding potential Mars toxicology
- Crew safety
- Mars sample handling
- Planetary Protection operations & considerations

A number of seminal references were identified as fundamental to the DOT's understanding of issues related to development of an informed Mars surface mission ConOps. These references were obtained for DOT review and spanned NASA, MEPAG, the National Academy of Science National Research Council (NAS NRC), and organizations responsible for Planetary Protection policy. One particular information resource was NASA's "Strategic Knowledge Gaps" (SKGs) associated with Mars. (SKGs are "gaps" in our knowledge and understanding regarding a number of issues associated with a specific exploration destination that must be addressed to enable a safe and effective future crewed mission.)

Finally, the DOT members toured the Sample Curation Laboratories at NASA Johnson Space Center with laboratory personnel, where a number of sample curation, containment and analysis facilities were shown.

III. Mars Mission Science-Driven Concept of Operations

In this section, the process by which a ConOps was developed for a Mars crewed long-duration surface mission driven by science requirements is described and some representative examples of crew surface activities devoted to achieving the science objectives are given. The goal of ConOps development was to construct representative operations for a DRA 5.0-like crewed mission to the surface of Mars, where the crew activities are driven by science objectives, in order to understand the capabilities, assets, and equipment needed to increase fidelity of architecture assessments. Below is a brief overview of the ConOps, to help provide context for the science-driven aspects that are discussed in more detail in the following section. As noted earlier, a NASA report describing the entire long-duration crewed Mars mission concept of operations in detail is in preparation by the broader DOT membership.

A. Groundrules & Assumptions Relevant to ConOps Development

Guiding groundrules and assumptions for developing the Mars mission ConOps were derived from DRA 5.0. In brief, the following was assumed:

- Number of crew = 6
- Mission duration on Mars' surface = 500 days
- Total mission duration = ~900 days
- Mission elements: Surface habitat and surface laboratory, two pressurized rovers for traverses, crew lander, Mars ascent vehicle, EVA capability for all six crew, surface power system, science instrumentation, deep drill, communications tower, cargo, robotic support
- Standard assumptions regarding crew activities over seven sols with one rest sol and numbers of EVAs

B. Mars Mission ConOps Development Process

A ConOps development process was created that began with DRA 5.0, the MEPAG HEM-SAG report, and the science information gathering activities as inputs into the process. A set of Mars mission phases was defined and served to form a conceptual framework for the full Mars mission ConOps. These Mars mission phases with associated estimates of sols (one sol = a Mars "solar day" = 24 hours + 39 minutes in "Earth time") were:

- Prior to cargo landing/cargo landing
- Post cargo landing (~2.25 years)
- Crew landing & acclimation (~30 sols)
- Local exploration (~30 sols)
- Regional exploration (~410 sols)
- Preparation for ascent (~30 sols)
- Post crew departure

The ConOps development process began with decomposing the science objectives into sets of associated activities. Sets of operations "building blocks" were then created that described the crew activities in detail with associated times-to-complete; operations associated with both EVA and intravehicular activity (IVA) were evaluated. The building blocks were constructed as two-hour "chunks" of crew time and, based on uncertainty associated with some operations, building blocks varied in their level of detail. For example, operations building blocks were created for installation of a meteorology data collection station, deployment of a spectrometer, drill rig setup and retrieval, and Mars surface sampling.

These building blocks were small segments of activities that were then repeated and "pieced together" to form larger groupings of crew activities. These groupings of crew activities were then integrated into a full mission within the Mars mission phases framework. This process produced a realistic, representative ConOps that could be traced to science objectives and constraints that could be used for deriving capability needs and element design.

C. Mars Science-Driven Concept of Operations Summary

Crew activities were defined for each of the mission phases described above. Primary attention was paid to developing the crewed surface exploration phases of the mission in detail, including detailed analysis of multiple traverses. Early in the process, it was decided that the crew's initial traverses would be conducted around the local landing site and later traverses would be conducted over longer durations (~15-day) and distances (~250-300 km). Analysis focused on a single high-priority Mars surface site (as identified by the MEPAG), Centauri Montes. It was assumed that the crew, upon landing on Mars' surface, would require 30 days to acclimate to the martian gravity environment. During this time, basic activities, such as unpacking stowed items, preparing the habitat for long-term Mars surface operations, activating landed instruments, and local (limited) EVAs, are conducted.

After acclimation, during the “Local Exploration” phase, the crew begins exploration and mapping of the local area, deploys central science stations (e.g., meteorology stations), performs initial atmospheric and climate science investigations, selects the location for and deploys the deep drill, and prepares systems for the upcoming long-distance traverse (e.g., mobility systems). A representative example of crew operations during this “Local Exploration” phase is given in Figure 1.

Sol	Crew 1 & 2	Crew 3 & 4	Crew 5 & 6
1	Local Exploration @ Landing Site	Test/Maintain/Stock Mobility Systems	Deploy Communications Tower
2	Test/Maintain/Stock Mobility Systems	Local Exploration @ Landing Site	Test/Maintain/Stock Mobility Systems
3	Deploy Central Science Station	Lab Analysis / Maintenance	Local Exploration @ Landing Site
4	Lab Analysis / Maintenance	Checkout/maintain In-Situ Resource Utilization System	Lab Analysis / Maintenance
5	Test/Maintain Mars Ascent Vehicle	Lab Analysis / Maintenance	Test/Maintain Mars Ascent Vehicle
6	Lab Analysis / Maintenance		Lab Analysis / Maintenance
7	Rest Sol	Rest Sol	Rest Sol

Figure 1. Example crew operations for six crew across seven sols during the “Local Exploration” phase of Mars surface operations.

During the next mission phase, “Regional Exploration,” the crew carries out multiple science-focused activities away from the habitat, such as multiple traverses for geology and geophysics activities, sample collection, balloon and chemistry campaigns, and laboratory analysis and curation. Over the course of this phase, four different traverse paths are followed through the region. It is assumed that each traverse is conducted using the two pressurized rovers with two crew in each rover (the four science-driven traverse paths examined were provided for the Centauri Montes site within the HEM-SAG report). The first traverse of each of the four traverse paths is conducted for *initial route characterization*. It was determined by the ConOps analysis that this approach permitted investigation of 23 sites with two hours of crew activity at each site. Information gathered during the initial traverses would be used to plan the follow-on traverses, during which science investigations are carried out, samples are taken, and instrumentation is deployed (e.g., meteorology stations or geophysics instrumentation left to gather data after the crew has departed). Our team created two categories of follow-on traverses: “geophysics-focused” (investigating six sites with eight hours of crew activity at each site) and shallow drilling-focused (investigating three sites with 16 hours of crew activity at each site). A representative example of crew operations during this “Regional Exploration” phase is given in Figure 2.

Sol 1	**Sol 2**	**Sol 3**	**Sol 4**	**Sol 5**	**Sol 6**	**Sol 7**	**Sol 8**
Traverse	**EVA**	**Rest Sol**	**EVA**	**IVA Characterization**	**Traverse**	**EVA**	**Rest Sol**
Traverse	**Local Seismometry**	**Rest Sol**	**Surface Measurements**	**Traverse**	**Traverse**	**Local Seismometry**	**Rest Sol**
IVA Characterization	**Drill Setup**	**Rest Sol**	**Target of Opportunity**	**Traverse**	**IVA Characterization**	**Drill Setup**	**Rest Sol**
IVA Characterization	**Surface Sampling**	**Rest Sol**	**Retrieve Drill & Sample**	**Traverse**	**IVA Characterization**	**Surface Sampling**	**Rest Sol**

Figure 2. Example crew operations for six crew across seven sols during the “Regional Exploration” phase of Mars surface operations (“Shallow-Drilling Focus” follow-on traverse).

Overall, the ConOps development activity indicated that the types of science-driven exploration activities, including traverses described in the HEM-SAG report, can likely be accomplished within the 500-day surface stay time available for a DRA 5.0-like mission.

IV. Science Considerations in a Crewed Mars Surface Science-Driven Mission

The most significant scientific challenge, and perhaps the most significant operational challenge, during a human Mars mission will be effectively dealing with Mars science samples. Science sample handling requires an integrated approach across a number of areas, such as: (a) traverse planning and execution, (b) sample acquisition and handling, (c) sample analysis, and (d) planetary protection. Cross-cutting themes of contamination control, low-latency telerobotic science, and crew autonomy are also briefly addressed in this section.

Sample acquisition and handling rests at the intersection of many considerations and includes a number of activities, such as containment, transport, and delivery, all of which are affected by contamination control, planetary protection, and crew safety. Sample acquisition is the beginning of the process, and methods of acquisition can be heavily influenced by precursor data (for example, if the sample is not from a potential “special region”; i.e., areas where possible martian life might exist or where terrestrial life could possibly survive and contaminate the environment). It may be possible to send humans into the area to collect the samples. Otherwise, alternative methods (e.g., real-time telerobotic sample acquisition and analysis) may be required to avoid the threat of introducing terrestrial contamination into the “special region.” Or, if it is confidently determined that contamination can be sufficiently controlled and/or that there is no threat posed by contamination, crew may be able to enter sensitive areas to acquire samples directly. Planetary protection policies and guidelines for human exploration continue to be developed and existing Committee on Space Research (COSPAR) guidance was used to inform this work; unquestionably, detailed guidance regarding human sample collection operations (including both surface and sub-surface sampling) will be required prior to fielding a human Mars mission, such that appropriate protocols and supporting systems can be developed.

The MEPAG HEM-SAG reference document provides a good starting point for establishing sample handling and analytical laboratory requirements. It indicates the need for different treatment across science disciplines, which requires further definition for higher fidelity operations assessments. Mars samples are required across multiple science disciplines, but the sample type and acquisition requirements vary. Geology generally requires surface and shallow subsurface samples. Atmospheric and climate science requires atmosphere (some at altitude) and surface samples to evaluate atmosphere/surface interactions. Geophysics requires distributed emplacement of instrumentation and long-term returned data. Astrobiology arguably has the most significant sampling challenges, e.g. sampling at depths perhaps 250 – 300 m down to a subsurface aquifer, data collection during drilling (e.g., via “downhole” instrumentation), and in-situ detection of unknown forms of life.

During this initial study, representative instrumentation was identified. Sensors and analytical instrumentation development is likely to be required (e.g., miniaturized biotechnology instrumentation for rapid in-field measurements during traverses). It would be advantageous to distribute analytical capability across numerous surface assets, such as in the rover, downhole during drilling, at the habitat area, and via “handheld” instruments used by the crew during EVA. These distributed analytical capabilities would vary in sophistication; for example, handheld instrumentation would be used by crew in-situ and would enable such activities as selecting the best samples for return to the habitat; the habitat and/or habitat area should contain advanced analytical capabilities, such as molecular sequencing, for which sample preparation will likely be a delicate and complex process. A separate astrobiology lab for analyzing Mars subsurface samples will reduce cross-contamination and help ensure crew safety.

This work is in the early stages and a number of key areas remain to be investigated in more detail. These include, for example, (a) crew safety protocols and their impact on surface element design; (b) operational details for sample collection, containment, transport, analysis, curation; (c) contamination control protocols and in-situ cleaning; and (d) planetary protection compliance and special regions operations strategies, including addressing contaminant leakage and transport and the potential for creating special regions (e.g., by melting ice or leaking water into the environment).

A. Traverses

The traverses envisioned in this Mars surface operations strategy are ambitious, in part to take advantage of the long duration of humans on the surface; the role of science in those traverses is a key component and driver of traverse planning and execution. Both walking and mobile traverse planning and execution will need to accommodate planetary protection protocols, particularly “special regions protocols,” perhaps by maintaining a TBD distance from special regions and/or adopting increasingly robust operational procedures to ensure that planetary protection and science sample integrity needs are met.

Long traverses will be critically beneficial for enhanced science return, so rovers will need to reliably cover large distances (e.g., 300 km) and allow for meeting proper operational needs for preserving sample intregity and ensuring planetary protection requirements. This appears to suggest a high degree of sample containment capabilities and perhaps analysis capabilities as well.

B. Sample Acquisition and Handling

The process of obtaining, handling, and analyzing samples will be an important part of ensuring acceptable science return – including in-situ real-time analyses with advanced miniaturized analytical equipment, potentially in association with shallow and deep drills. A significant challenge for Mars surface science operations with crew is preserving science sample integrity in what will likely be an uncertain environment, particularly when acquiring samples from special regions. Non-special region sample acquisition, which may be executed by a crew member using a tool or glove, will still likely require contamination control protocols that could vary depending on the particular sample, its purpose, the acquisition method, and analytical techniques that might allow contamination effects to be removed, or at least sufficiently understood as to not adversely impact science investigations.

Based on our limited knowledge at this time, a conservative analytical posture is to assume that acquiring samples in special regions and from the subsurface will require substantial caution and operational diligence to meet planetary protection needs, science needs, and crew safety needs. Telerobotic sample acquisition is one way to help address these risks, but will require very clean sample acquistion assets and methods, with the ability to thoroughly re-clean and/or replace contaminated assets on the Mars surface. Extremely robust sample containment, along with some analytical capabilities within such containment environments (possibly limited to passive, "non-intrusive" analyses) will be beneficial on traverses and at the base lab and for returning samples to earth.

Drilling presents unique challenges. An existing guideline suggests that drilling deeper than 5 m invokes “Special Region” considerations. However, if ice may be as shallow as 3-5 m (as per some recent findings), and if drilling through ice effectively creates a special region by melting ice, then the 5 m sub-surface threshold might need to be reevaluated. At presently demonstrated drilling rates, it may take more than 500 sols to drill down to 300 m, so additional technology development, more power, and/or autonomous drilling before crew arrives may be required. One estimate suggests that dedicated drilling equipment could be in the 700 to 1000 kg range, with additional mass for other functions (e.g., borehole casing and mobility), possibly reaching a range of 2200 kg for a robust deep drilling capability.

C. In-Situ Sample Analysis

Analyzing samples on the surface of Mars could turn out to be an important enabler for science return, including the need to determine which samples should be brought back to earth for more in-depth analysis. Being able to (a) analyze samples at their location with minimized disturbance, (b) analyze samples near a sampling location (e.g., to reduce transport time and impacts, such as a sample returned from depths to the surface), as well as (c) conduct analysis at a lab where more robust analytical tools would be available, are all important in-situ science analysis capabilities with different implications.

Representative instrumentation was identified, recognizing that some sensors and analytical instrumentation development may be required. Microminiaturized analytical instrumentation from biotechnology industry can be leveraged. Distributed analytical capability for the rover, downhole during drilling, at habitat area, and “glove-size” for EVA crew, will all help address the need for analysis capabilities at different locations. For example, a small analytical laboratory in the rover could be used during traverses. Downhole sensors are required for data collection during drilling for subsurface samples. Small handheld instruments will be needed by crew during EVA and should be designed to accommodate human factors associated with suited crew and EVA operations in general. A separate analytical capability at the habitat area, such as a separate astrobiology lab for analyzing Mars subsurface samples, can help reduce cross contamination and contribute to crew safety.

D. Planetary Protection

The integration of planetary protection policy and controls into missions to the Moon (largely as practice for future deep space missions) and other celestial bodies such as Mars is an important operational consideration. Meeting planetary protection needs will be a key challenge for Mars surface science strategies, particularly with respect to the exploration of special regions. There are formal COSPAR principles and implementation guidelines in place for human missions to the Moon and other celestial bodies, but there are not yet defined protocols, technologies, or operations details, although they are beginning to be developed. Proactively integrating planetary protection information and policies early in mission planning will take advantage of synergies and cross-cutting efforts in many development activities, and can reduce high costs that might otherwise be incurred late in the program life-cycle.

Planetary protection controls have been studied extensively in coordination with both NASA and International agencies for many years and it is recognized that such controls must be integrated into mission protocols and are often synergistic with other mission needs. Such controls have implications for many aspects of crewed Mars missions and impact both robotic and human aspects of such missions, including: (a) forward and backward contamination; (b) chemical pollutants detection and measurement; (c) biological monitoring, including microbial identification; (d) equipment decontamination and sterilization; (e) sample containment and handling; (f) advanced life support systems (ALS), including closed-loop recycling capabilities and waste handling and disposal; (g) EVA equipment, including suits and associated ALS and ingress/egress; (h) subsurface drilling equipment and operations; (i) in-situ resource utilization systems; (j) laboratory–habitat separation; and (k) quarantine protocols.

Missions to bodies like the Moon and asteroids, which are not habitable or not likely to have putative indigenous extraterrestrial life, are not highly constrained by planetary protection considerations, but they can nonetheless provide useful testbeds for technology and operations and may serve as stepping stones to overall mission success for missions to Mars. Such details are presently being explored by HAT.

E. Cross-Cutting Themes

There are at least 3 important cross-cutting themes that emerge when considering details of long-duration Mars surface science operations: (1) contamination control, (2) low-latency telerobotic science, and (3) crew autonomy. These themes touch almost every aspect of Mars surface science operations and could make an important difference to how science return is affected and how most surface operations are executed.

Contamination control is certainly required for science reasons (and in some cases may be more stringent than planetary protection protocols) and it also overlaps with crew safety and system performance. Crewed mission surface assets, such as habitats, EVA suits, and pressurized rovers, could be a significant source of contamination, due to venting, out-gassing and cleanliness levels associated with crew presence. Cleaning and verification methods will almost certainly be required to clean and track contaminants, including dust from EVA suits, mobility assets, and other assets that may come into contact with martian material.

Low-latency telerobotic science operations has the potential to address a number of contamination control and planetary protection issues, including its use as a possible strategy for reducing the potential for contamination when exploring at or near special regions. Using autonomous, semi-autonomous and/or small telerobotic robotic rovers for scouting traverses ahead of crew may be a useful reconnaissance technique for both planetary protection and crew safety reasons, and may contribute, as well, to resource management optimization (e.g., reducing consumable consumption).

Crew autonomy is another key cross-cutting challenge regarding Mars surface science operations, because the large communications delay will require the crew to plan and perform many science tasks without direct timely intervention from ground support on earth. Striking the operational balance between crew autonomy and earth support will be a key challenge that can be tested in prior missions (e.g., on ISS and in cislunar space) and is something the NASA HAT is beginning to investigate in more detail.

V. Conclusion & Key Findings

An integrated ConOps was developed for a long-duration human Mars surface mission and was found to aid in understanding interdependencies between functional requirements and the capabilities needed to meet requirements associated with conducting the mission with a “science-driven” focus. The nominal 500-Sol surface duration is technically feasible and provides sufficient time to address science and exploration objectives, with several notable caveats.

The deep drilling for sampling activity, in particular, was problematic in that current drilling technology options and operations do not fit within the mass allocation or time available as stated in DRA 5.0. Drilling activities have the potential to be significantly influenced by Mars special region constraints and a number of technical and operational concerns were noted, including the time needed to drill to the required depth and how to handle samples without breaking planetary protection protocols or compromising the integrity of science samples. This requires further analysis to find a solution that will fit within overall mission constraints.

The ConOps also helped the HAT DOT identify potential missing mass from the overall surface manifest, e.g. science lab external to habitat, contamination control (e.g., via sterilization) and verification, suit maintenance area, robotic rovers for exploring special regions (including a potential requirement for a dedicated rover to support deep drilling operations). Integrating planetary protection considerations into mission operations plans, architectures and systems, including nearer-term missions in cislunar space that can feed forward to Mars, will help reduce technical, operational and programmatic risks down the road.

Acknowledgments

The authors wish to acknowledge the primary members of the HAT DOT who participated in this study: Mr. Larry Toups, NASA JSC (study co-lead with the first author); Dr. Stephen Hoffman, SAIC; Mr. David Reeves, NASA LaRC; Ms. Michelle Rucker, NASA JSC; and Mr. David North, NASA LaRC. The authors also acknowledge the contributions of a number of experts in various fields, both NASA and contractor, who contributed their time, as needed, to the study effort. In addition, the authors gratefully acknowledge the time that members of the science community devoted to our team in helping us understand the operations requirements of the science community: Dr. Dean Eppler, Dr. Mary Sue Bell, Dr. Paul Niles, and Mr. John Gruener (all NASA JSC), Geology; Dr. Nicholas Schmer (NASA GSFC), Geophysics; Dr. Joel Levine (formerly NASA LaRC, presently with the College of William & Mary), Atmospheric & Climate Science; Dr. Peter Doran (University of Illinois at Chicago), Astrobiology; Dr. Catharine Conley (NASA Headquarters) and Dr. Margaret Race (SETI Institute), Planetary Protection; and Mr. Michael Calaway (NASA JSC), Sample Curation & Contamination Control.

References

[1] Mars Analysis Planning Advisory Group (MEPAG) Human Exploration of Mars-Science Analysis Group (HEM-SAG), "*Planning for the Scientific Exploration of Mars by Humans"* (2008).

[2] Drake, Bret G.., Editor, "Human Exploration of Mars Design Reference Architecture 5.0," NASA/SP-2009-566.