June 24, 2012

Concepts and Approaches for Mars Exploration[1]

- Report of a Workshop at LPI, June 12-14, 2012 –

Stephen Mackwell[2] (LPI)

Michael Amato (NASA Goddard), Bobby Braun (Georgia Institute of Technology), Steve Clifford (LPI), John Connolly (NASA Johnson), Marcello Coradini (ESA), Bethany Ehlmann (Caltech), Vicky Hamilton (SwRI), John Karcz (NASA Ames), Chris McKay (NASA Ames), Michael Meyer (NASA HQ), Brian Mulac (NASA Marshall), Doug Stetson (SSECG), Dale Thomas (NASA Marshall), and Jorge Vago (ESA)

Executive Summary

Recent deep cuts in the budget for Mars exploration at NASA necessitate a reconsideration of the Mars robotic exploration program within NASA's Science Mission Directorate (SMD), especially in light of overlapping requirements with future planning for human missions to the Mars environment. As part of that reconsideration, a workshop on *"Concepts and Approaches for Mars Exploration"* was held at the USRA Lunar and Planetary Institute in Houston, TX, on June 12-14, 2012. Details of the meeting, including abstracts, video recordings of all sessions, and plenary presentations, can be found at *http://www.lpi.usra.edu/meetings/marsconcepts2012/*. Participation in the workshop included scientists, engineers, and graduate students from academia, NASA Centers, Federal Laboratories, industry, and international partner organizations. Attendance was limited to 185 participants in order to facilitate open discussion of the critical issues for Mars exploration in the coming decades. As 390 abstracts were submitted by individuals interested in participating in the workshop, the Workshop Planning Team carefully selected a subset of the abstracts for presentation based on their appropriateness to the workshop goals, and ensuring that a broad diverse suite of concepts and ideas was presented. In order to accommodate interest from those who were not able to attend the workshop, the plenary sessions and 3 breakout sessions were streamed live through the web, and recorded for future viewing. Remote viewers were able to post questions and comments and local subject-matter experts provided real-time responses.

Presentations and discussion focused on 1) near-term concepts for robotic Mars missions that might meet the 2018 and 2020 launch opportunities and that are compliant with the Mars community consensus science goals, especially as delineated in the 2013-2022 Planetary Science Decadal Survey; and 2) longer-term technology development needs for future robotic and human missions to Mars, noting the potential synergies between the NASA Science Mission Directorate (SMD), the Human Exploration and Operations Mission Directorate (HEOMD) and the Office of the Chief Technologist (OCT) programs that may significantly reduce cost and mission risk.

The general consensus was that the workshop was a great success, with presentations on cutting edge science, technology and mission concepts, dynamic and inclusive discussions on how to meet Mars

[1] *This document is LPI contribution #1676.*

[2] *mackwell@lpi.usra.edu*

exploration goals under the current fiscal environment, and delineation of needs and solutions for the technology challenges of the future. The discussion periods were free-ranging and boiled over into the hallways after the sessions. The Breakout Panels captured the essence of the discussion and presented summaries in a plenary session on Thursday afternoon, where all workshop participants were able to raise additional thoughts and ideas. Using the Breakout Panel presentations and interactions with meeting participants, the Integration Team met on Thursday late afternoon and Friday morning to assimilate the information into the meeting report. The Team identified several broad themes that captured the essence of the meeting and are summarized below.

Presentations and discussion in all of the Breakout Groups made a strong case that missions can be flown to Mars in the coming decade that would provide credible steps toward Mars Sample Return, while making significant advances in our understanding of Mars and validating key technologies. Although not as comprehensive as MAX-C, the mission concepts identified were considered by the workshop participants to represent feasible, affordable, and potentially productive steps toward MSR that can be taken using a mission launched in the 2018 or 2020 windows. In particular, in the last several years, through both NASA and commercial activities we have seen advances in systems for sample acquisition and organics detection that greatly increase the possibilities of significant decadal science advancements on smaller size missions such as fixed lander or MER class rover missions. In addition to compelling science, such missions would provide data to reduce cost and technical risk for future robotic and human exploration of the Martian surface and interior. Numerous participants argued that it would be highly desirable for NASA to undertake, as part of its program reformulation, a study of the trade space of potential near-term missions in order to create the optimal program architecture leading to Mars Sample Return and human missions to Mars. Such missions might be considered as a new generation of Mars Scouts.

Numerous speakers suggested that significant program benefits would be gained through integrated SMD/HEOMD nearer-term and longer-term technology investments as part of the reformulated Mars program performed in collaboration with OCT. It was felt that these investments are enhancing for the attainment of Decadal science goals and enabling for eventual human missions to Mars. As was clear from the presentations, technology advances since the inception of the 2013-2022 Decadal Survey have significantly increased the capabilities of small to medium sized missions. In the long term, there are substantial benefits to creating scalable solutions usable for both near-term robotic and future human missions.

Many speakers noted how international partnerships can be highly enabling, especially as Mars exploration missions become increasingly complex. Such partnerships may be at the mission or instrument level, and/or involve participating scientists. A strong connection with potential international partners is essential early in mission planning and must be maintained throughout mission implementation. For relatively modest cost, it was suggested that a reinvigoration of the US participation in ESA's ExoMars mission could do much to repair relations between Europe and the US in robotic planetary exploration.

Many participants noted that a reformulated robotic exploration program must also be balanced by a continuing commitment to a vigorous and well-funded R&A program, including studies of Martian meteorites and development of improved sample analysis techniques. In addition, sustenance of a strong program of education and public outreach is needed to maintain and grow public appreciation and support for planetary exploration.

Introduction

The Concepts and Approaches for Mars Exploration workshop was sponsored by NASA to actively engage the technical and scientific communities in the early stages of a longer-term process of collaboration that bridges NASA's Science Mission Directorate, Human Exploration and Operations Mission Directorate, and Office of the Chief Technologist. It was held at the USRA Lunar and Planetary Institute in Houston, Texas, on June 12–14, 2012, and included scientists, engineers, and graduate students from academia, NASA Centers, Federal Laboratories, industry, and international partner organizations. This workshop formed a critical part of a reformulation of the Mars Exploration Program, providing a forum for community input on near-term mission concepts and longer-term foundations of program-level architectures for future exploration of Mars. Discussion at the workshop focused on the development of high-pay-off mission(s) potentially beginning with the 2018 launch opportunity, which are responsive to the scientific goals articulated by the National Research Council Planetary Science Decadal Survey (*Visions and Voyages for Planetary Science in the Decade 2013–2022*, NRC Press 2012), to the Mars Exploration Program Analysis Group Goals, and to the President's challenge of sending humans to the vicinity of Mars in the decade of the 2030s.

The format of the meeting allowed brief oral presentation of concepts and ideas by individuals selected to participate in the meeting within one of three Breakout Groups: Technology and Enabling Capabilities; Human Exploration and Precursors; and Science and Mission Concepts. Selection of participants at the workshop was limited to 185 people, and was based on the review of abstracts submitted to the workshop through the meeting website. A Workshop Planning team, chaired by Stephen Mackwell (LPI), selected abstracts for presentation from the 390 submissions, based primarily on retention of the broadest range of concepts and ideas within the stated scope of the workshop. Thus, when multiple abstracts were received on a similar concept, only one was generally accepted and the presenter was encouraged to speak to the concept, rather than promoting their particular approach or architecture. As such, the invited presenters (listed in Appendix 1) represent a diverse group of innovators in science, technology, and human exploration, but not necessarily a balanced cross section of the Mars exploration community. Summary reports (see Appendix 3) from the Breakout Groups were presented by the Breakout Panels in a plenary session on the last day of the meeting, which formed the basis of this report.

Further details about the workshop, including the presentation videos, the summary reports, and a compilation of the abstracts, can be found at *http://www.lpi.usra.edu/meetings/marsconcepts2012/.*

Background

In addition to briefings from NASA and ESA on their current programs for the robotic exploration of Mars, the workshop attendees received presentations on the defining community consensus documents that relate to the robotic and human exploration of Mars in the coming decades. A summary of these background documents and activities is provided in Appendix 2, as it pertains to the workshop goals.

Of particular note, the 2013-2022 Planetary Decadal Survey identifies the most important science in this discipline to be addressed in the coming decade. For Planetary Sciences, the Decadal Survey identified 3 broad unprioritized crosscutting themes (Vision and Voyages, Summary, p. 11):

- Building new worlds – understanding solar system beginnings;
- Planetary habitats – searching for the requirements for life;
- Workings of solar systems – revealing planetary processes through time.

The Mars Panel, in Chapter 6 of the Decadal Survey, identified a set of major science goals for the exploration of Mars, which contribute substantially to all three of the Decadal Survey crosscutting themes (Vision and Voyages, Chapter 6, p. 141-142):

- *Determine if life ever arose on Mars* - Does life exist, or did it exist, elsewhere in the universe? This is perhaps one of the most compelling questions in science, and Mars is the most promising and accessible place to begin the search;
- *Understand the processes and history of climate* - Climate and atmospheric studies are key to understanding how the planet may have been suited for life and how major parts of the surface have been shaped, and are directly relevant to our understanding of the past, present, and future climate of Earth. Additionally, characterizing the environment of Mars is also necessary for the safe implementation of future robotic and human spacecraft missions to the planet;
- *Determine the evolution of the surface and interior* - Insight into the composition, structure, and history of Mars is fundamental to understanding the solar system as a whole, as well as to providing context for the history and processes of Earth.

Based on their deliberations, the Mars Panel identified: *"The major focus of the next decade will be to initiate a Mars Sample Return (MSR) campaign, beginning with a rover mission to collect and cache samples, followed by missions to retrieve these samples and return them to Earth. It is widely accepted within the Mars science community that the highest science return on investment for understanding Mars as a planetary system will result from analysis of samples carefully selected from sites that have the highest scientific potential and that are returned to Earth for intensive study using advanced analytical techniques."* (Vision and Voyages, Chapter 6, p. 140-141)

Mars holds answers to many compelling planetary science questions, and the Mars science goals are well aligned with the broad crosscutting themes of solar system exploration. Of critical significance is the excellent preservation of the geologic record of early Mars, the period >3.5 billion years ago when life began on Earth – an epoch whose record is largely lost on our own planet. Thus, Mars provides the opportunity to address questions about how and whether life arose elsewhere in the solar system, about processes of planetary evolution on a planet that has undergone major changes through time, and about the potential coupling between biological and geological history.

Workshop Structure and Preparation of this Report

The agenda for the workshop and access to abstracts is provided at the LPI web site: *http://www.lpi.usra.edu/meetings/marsconcepts2012/agenda/.* On Tuesday morning, the participants were provided with overview presentations on:

- NASA's Robotic Mars Activities – Doug McCuistion (NASA HQ)
- ESA's Mars Activities – Jorge Vago (ESA)
- Precursor Strategy Analysis Group – Dave Des Marais (NASA Ames)
- Planetary Decadal Survey – Stephen Mackwell (LPI)

After this Plenary Session, the participants separated into 3 Breakout Groups, each lead by a Panel comprising representatives of science, engineering and human exploration:

- Technology and Enabling Capabilities, with panelists: Michael Amato (NASA Goddard), Vicky Hamilton (SwRI), Brian Mulac (NASA Marshall), Bethany Ehlmann (Caltech)
- Human Exploration and Precursors, with panelists: John Connolly (NASA Johnson), Chris McKay (NASA Ames), John Karcz (NASA Ames)
- Science and Mission Concepts, with panelists: Doug Stetson (SSECG), Steve Clifford (LPI), Jorge Vago (ESA)

The Breakout Groups comprised brief 10-minute presentations by the participants, plus extended discussion periods on the session focus area, led by the Panel. The Groups met until noon on Thursday. The Plenary Session on Thursday afternoon involved presentations by the Breakout Panels, summarizing the activities from their sessions and providing overarching perspectives based on the presentations in the breakouts and the associated discussion. These presentation materials are provided as Appendix 3 of this report.

Both Plenary Sessions and Breakout Sessions were broadcast live to the web using LiveStream. In each meeting room, a moderator and subject-matter expert provided responses to questions submitted through LiveStream by participants viewing the workshop from remote locations. Some of the questions were incorporated in the panel discussions during the Breakout Sessions.

The Integration Team (listed as authors of this report) met on Thursday afternoon after the final plenary session and on Friday morning to integrate the results from the 3 Breakout Groups and prepare this report. To ensure that the sense of the breakout discussions was fully integrated into the report, all members of the Breakout Panels were included in the Integration Team.

Summary of Workshop Results

This workshop had as a major goal the identification of new concepts and ideas for Mars exploration that might permit optimal retuning of the Mars program in light of current harsh fiscal realities. Such retuning would, of course, have to be consistent with the community consensus planning documents for Mars exploration. The Decadal Survey anticipated a changing fiscal environment and provided some guidance for how to deal with such a situation: *"It is also possible that the budget picture could be less* *favorable than the committee has assumed. If cuts to the program are necessary, the first approach should be to descope or delay flagship missions. Changes to the New Frontiers or Discovery programs should be considered only if adjustments to flagship missions cannot solve the problem. And high priority should be placed on preserving funding for research and analysis programs and for technology development."* (Vision and Voyages, Executive Summary, p. 7)

Using input from the submitted abstracts, the presentations at the workshop, the panel discussions, and the appropriate planning documents discussed in the Background Section, the Integration Team had a wide-ranging discussion of options for the future exploration of Mars. These discussions broke into 2 discrete time frames: the near-term, which encompasses the next decade of robotic exploration activities, focusing on possible missions for the 2018 or 2020 launch opportunities, and the longer-term, with a focus on technology developments and activities that will lead to cost and risk reduction for both robotic and human missions to the Mars environment up to and during the 2030s.

Near-term Mars exploration

NASA has identified a potential robotic flight opportunity for either the 2018 or 2020 launch windows for Mars. This mission would be expected be consistent with the recommendations of the 2013-2022 Planetary Science Decadal Survey, as summarized in the Background Section and Appendix 2.

The Mars Chapter of the Decadal Survey not only identified the initiation of a Mars Sample Return campaign as the highest priority for the robotic exploration of Mars in the 2013-2022 decade, it also provided substantive arguments in favor of an overall mission design that would bring back "*samples carefully selected from sites that have the highest scientific potential".* Such careful sample and site selection to ensure optimal samples for return that address the highest priority goals for Mars exploration would appear to preclude many simpler architectures for Mars sample return. It must also be noted that one of the highest priority science goals for Mars exploration is to determine if life has existed or does presently reside on or in that planet. Of note, the Planetary Decadal states *"Crucially, the martian surface preserves a record of earliest solar system history, on a planet with conditions that may have been similar to those on Earth when life emerged. It is now possible to select a site on Mars from which to collect samples that will address the question of whether the planet was ever an abode of life."* (Vision and Voyages, Executive Summary, p. 1)

Based on the presentations and discussion at the workshop, it is clear that important scientific and technological advances have been made since the initiation of the Decadal Survey, and that these may bear on technical and programmatic decisions regarding Mars Sample Return. They include strong evidence for transient present-day liquid water and salty brines on or near the surface; identification of substantial mid-latitude ice deposits; improved understanding of aqueous processes and their surface manifestations, including gullies and recurring slope lineaments; refinement of techniques for biological analysis compatible with small surface missions; recognition from orbit of sites with key type stratigraphies that collectively preserve a record of a half-dozen distinctive ancient Mars environments; and thorough analysis of candidate Mars Science Laboratory (MSL) landing sites resulting in the selection of the Gale Crater target. It is important that reformulation of the Mars program, and in particular the strategy for Mars Sample Return, be conducted in light of these and other recent advances.

While it appears unlikely that the budget for the coming decade would support a MAX-C rover as the first mission of the MSR campaign, as envisioned in the Decadal Survey, several mission concepts were identified that could enhance Mars sample return by improving science return, identifying prime target areas, increasing technology readiness, and otherwise reducing MSR mission cost and risk. Such missions could also make significant contributions toward eventual human missions to Mars. Although not as comprehensive as MAX-C, these mission concepts were considered by the workshop participants to represent feasible, affordable, and potentially productive steps toward MSR that can be taken using a mission launched in the 2018 or 2020 windows. Listed from lowest to highest scientific contribution to MSR, these missions include:

- An orbital mission that would advance or enable efficient MSR mission implementation. One possible example would be a mission that is capable of very accurate location of vent sites for trace gases (including methane), perhaps using LIDAR in combination with other techniques. If found and accessible, later sample return from such a vent site could address questions of biological or non-biological origin for methane in the Mars atmosphere. Depending on budget availability, such an orbital mission could also map the surface using imaging radar and/or probe the subsurface with advanced radar sounding, potentially focusing on trace gas source regions or the potential availability of subsurface water/ice. The spacecraft would include data relay capability (Com Orb) with sufficiently long lifetime to contribute to future surface missions through much of the 2020s. It should be noted that while this mission is very similar to ESA's Trace Gas Orbiter mission, it was not regarded as a pre-cursor to MSR in the Decadal Survey, and, based on Decadal Survey guidelines, would likely be better suited to the Discovery Program.
- One or more static landed missions, similar to Phoenix (PHX), with state-of-the-art organic detection and chemical characterization payloads and probably including deep access capabilities and/or coring drills. This payload would be designed to detect prebiotic markers and evidence for past or present life in surface and subsurface samples. Positive detection would dramatically advance the scientific foundation for Mars Sample Return in terms of site and sample selection criteria. Such a lander or landers could be targeted to polar or near-polar regions, where the landing site would be representative of the surrounding region, particularly in the subsurface, or deltas and outflow channels, where the sedimentary deposits are composed of materials from the surrounding region and may have concentrated organic matter.
- One or more MER-class rovers with modest range, equipped with similar astrobiology-focused payloads and drilling/coring capability as the static landers above. The mobility of this platform would increase the probability of finding optimal locations to sample. Depending on the available budget, sending multiple such rovers to diverse and widely separated regions, informed by Mars orbiters and, perhaps, MSL and/or ExoMars results, could represent a major step toward MSR at lower cost than MAX-C. Based on the technological advances made since the initiation of the Decadal Survey, much discussion at the workshop centered on the potential of this mission class to capture a large subset of the MAX-C mission objectives.

The surface missions identified could also lead directly to the accomplishment of sample return as described the Decadal Survey. In particular, in the last several years, through both NASA and commercial activities we have seen advances in systems for sample acquisition and organics detection that greatly increase the possibilities of significant decadal science advancements on smaller size missions such as fixed lander or MER class rover missions. The cored samples from surface missions could be stored and monitored to demonstrate that capability and, if deemed of high priority, could be collected during a potential future sample return mission to the same region. The benefits to a later MSR mission campaign could justify selection in the coming decade, while providing significant science return in their own right.

Trade Space of Near-Term Mission Concepts

Figure 1 shows the trade space of these orbital and surface mission concepts in terms of their relative cost and the degree to which they can advance the scientific foundation for sample return. It is important to note that it was not within the scope of the workshop to explicitly assess the cost of proposed missions or investigations in any rigorous manner; the cost categories shown are approximate and are derived by analogy with similar actual or proposed missions. Likewise, assessment of the degree to which the various missions contribute to Mars Sample Return is subjective and highly dependent on the specific mission concept. Nonetheless, the consensus of the workshop is that this is a reasonable and representative picture of the types of missions that NASA should consider during reformulation of the Mars program and planning for sample return.

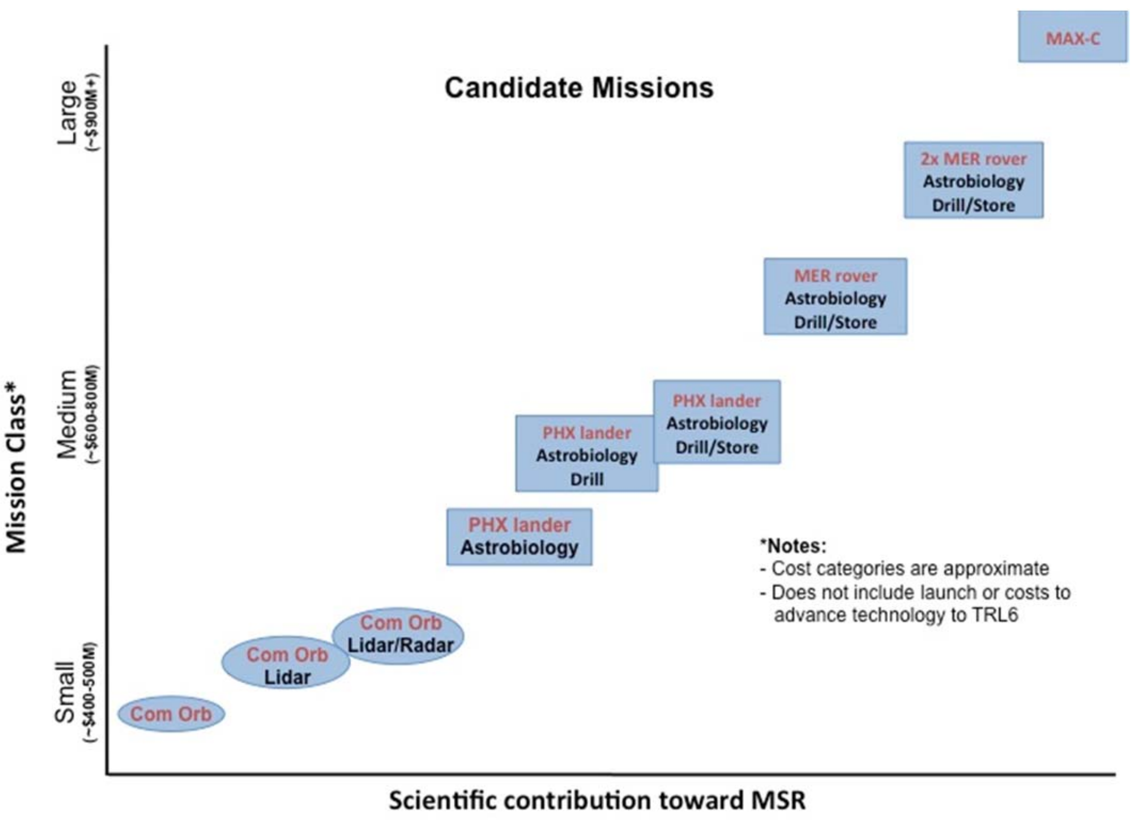

Fig. 1

The optimal Mars Sample Return architecture depends not only on improved scientific knowledge of sites and samples, but also on readiness and possible demonstration of key technologies. Technology readiness for Mars Sample Return and eventual human exploration was a major focus of both the Decadal Survey and this workshop, and the results are summarized later in this report. Near-term missions represent not only opportunities to advance scientific knowledge, but also to validate key technologies that are important for sample return. **Figure 2** shows how the proposed orbital science missions could be augmented to advance technology readiness, benefiting future robotic and human exploration missions. Two sample technology focus areas – optical communications and autonomous rendezvous and docking – were selected as potentially high-payoff technologies that could be ready for validation at Mars in the near term. The figure provides an estimate of the additional cost and the overall increased benefit toward sample return due to inclusion of one or both of these technologies on the instrumented science orbiters. While subjective, in the opinion of the workshop participants this represents the type of science/technology/cost trade that NASA should consider in Mars program reformulation.

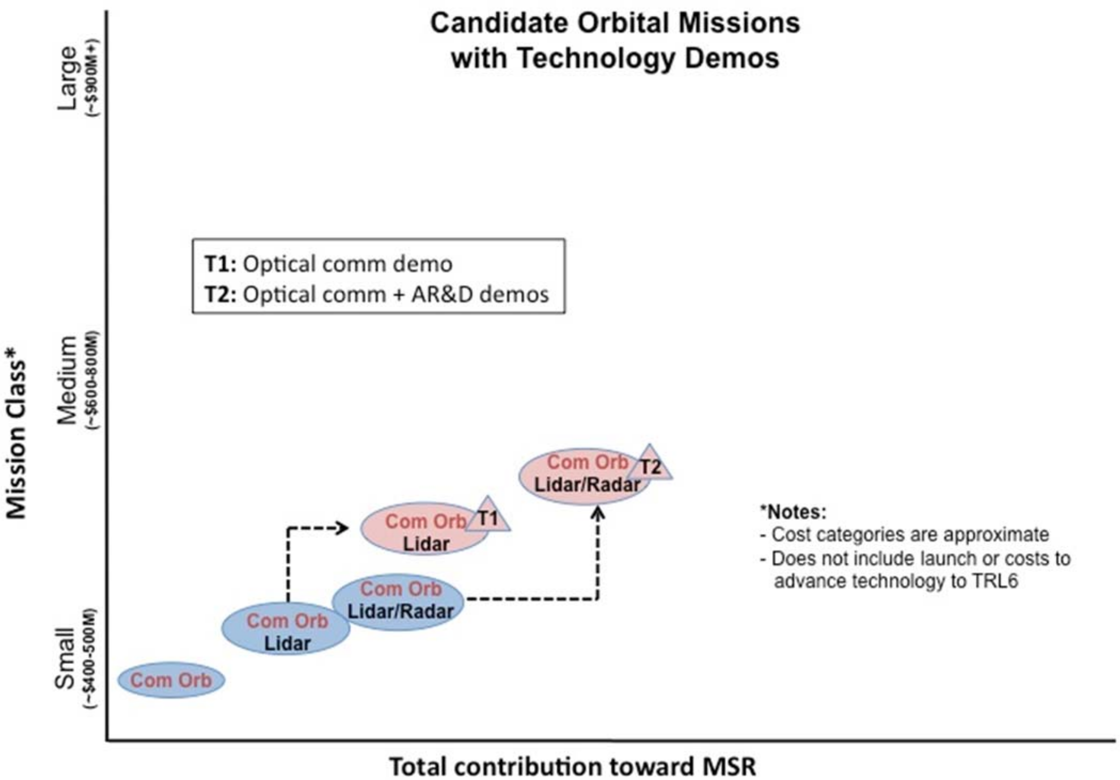

Fig. 2

Similarly, **Figure 3** shows how the proposed landed missions could be augmented to advance technology readiness, benefiting future robotic and human exploration missions. In this case we selected the Mars Ascent Vehicle (MAV) and Pinpoint Landing (sub-km accuracy) as technologies that could significantly advance readiness for MSR and be ready for validation at Mars during the mid-2020s. The plot indicates the relative increase in cost and improvement in overall readiness of MSR for inclusion of one or both technologies on the static lander platform with the core astrobiology payload. Once again, while subjective, the consensus of the workshop is that these are realistic options that should be considered by NASA, and that it is important that near-term missions be assessed in terms of both their scientific and technological benefits for future missions.

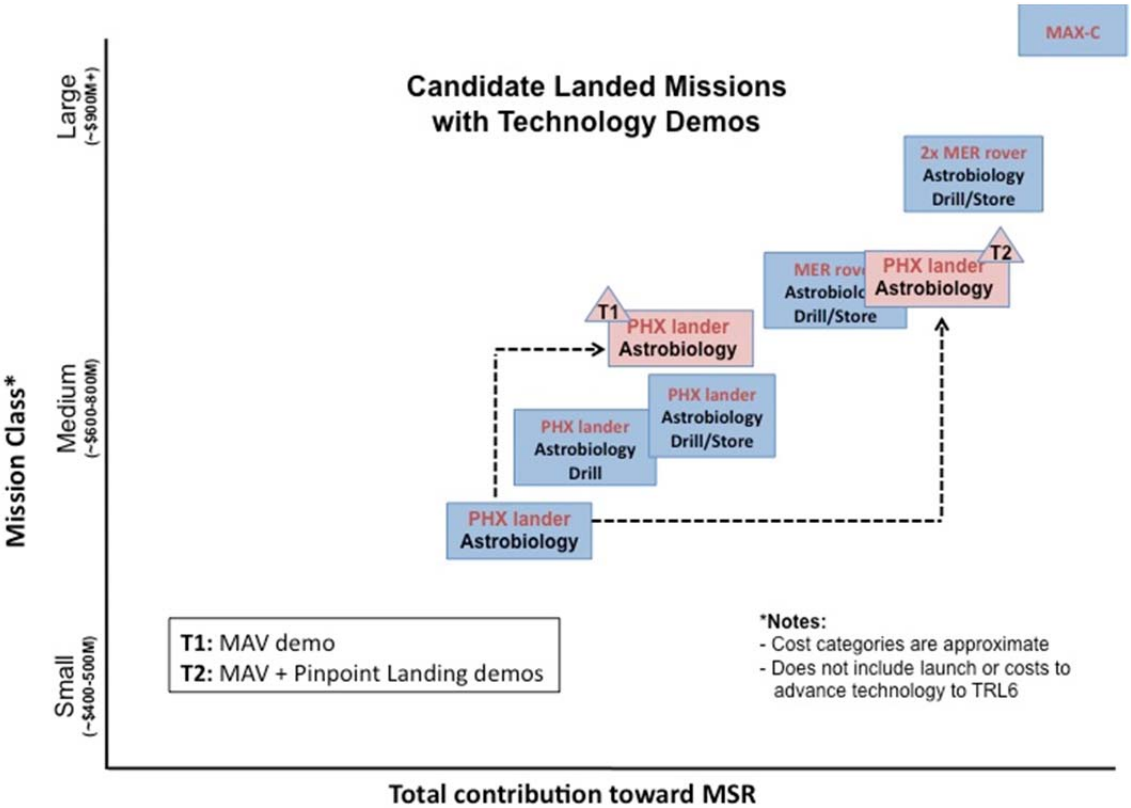

Fig. 3

In summary, the presentations and discussion in all of the Breakout Groups made a strong case that missions can be flown to Mars in the coming decade that would provide credible steps toward Mars Sample Return, while making significant advances in our understanding of Mars and validating key technologies. In addition to compelling science, such missions would provide data to reduce cost and technical risk for future robotic and human exploration of the Martian surface and interior. Numerous participants argued that it would be highly desirable for NASA to undertake, as part of its program reformulation, a study of the trade space of potential near-term missions in order to create the optimal program architecture leading to Mars Sample Return and human missions to Mars. Such missions might be considered as a new generation of Mars Scouts.

Longer-term Mars exploration and the Role of HEOMD

Robotic missions to Mars will continue beyond the current decade, following the recommendations of the Planetary Decadal Survey, the MEPAG Goals document, and the P-SAG. Such missions will likely involve further characterization of the Mars environment, as well as robotic precursor activities for human exploration. Activities, such as sample return missions, may be significantly enabled by new technologies that are also critical for future human exploration missions. In particular, the Decadal Survey indicates *"Looking ahead to possible missions in the decade beyond 2022, it is important to make* *significant near-term technology investments now in the Mars Sample Return Lander, Mars Sample Return Orbiter, Titan Saturn System Mission, and Neptune System Orbiter and Probe."* (Vision and Voyages, Executive Summary, p. 7)

NASA has the goal of humans to the Mars environment in the 2030 timeframe. In order to achieve this goal, there will need to be significant advances in a wide range of fields, in order to reduce cost and technical risk, and minimize threats to astronaut health and safety. The knowledge acquired through robotic missions is critical for enabling safe, cost-effective human missions. Additional instrumentation on science and robotic precursor missions will produce more precise characterization of the Martian environments, which will benefit future human missions through mitigation of cost risk and improved astronaut safety. High-resolution mapping of surface features and mineralogy, and subsurface sounding and imaging radar will enable better site selection and identification of potential resources, with benefits to closing Strategic Knowledge Gaps (SKGs) and achieving overall mission success. The demonstration of key technologies that are enabling for future human missions will both increase the capabilities for robotic missions and reduce risk for human missions.

Synergy in enabling technologies between robotic and human missions increases as the robotic missions become more ambitious. This synergy can manifest itself in two ways: 1) technologies, such as entry, descent, and landing systems, when scaled for application to human missions, enable greater payload mass for robotic missions; and 2) leveraging technologies needed for human missions, such as *in situ* resource utilization (ISRU) and LOX-methane propulsion systems, can benefit a Mars sample return mission, due to the potential for reduction in launch and entry mass, hence reducing mission cost. In order to assure timely and sufficient technology maturation for eventual human missions, commitment to collaboration and cost-sharing on an equitable basis is needed between SMD and HEOMD on future robotic missions, as well as collaboration with the OCT to prioritize technology programs of common benefit.

During the workshop, numerous presentations identified technological developments that can and will greatly facilitate future Mars robotic and human missions. The technological maturity of the various concepts was highly variable, with many concepts relatively mature while others were barely beyond concept stage. Promising technology investments for Mars exploration could be separated into nearer-term and longer-term requirements, as delineated below:

Technology investments to make now for flight in the 2020s:

- Continued investment into the maturation of compact sample acquisition, retrieval, handling and storage systems (i.e., laboratory/field demonstrations on Earth)
- *In situ* sample analysis and context instruments - nearer term missions at lower cost also require capable lower volume and mass *in situ* sample analysis instruments. MIDDP has not been funded in some time and PIDDP and ASTID have experienced low selection rates that may not allow robust development of required solutions as our mission approaches drive to smaller and lower cost solutions. The new combined program should have enough funding to allow the mid-TRL advancement of elements needed for nearer-term mission options.
- Precision landing (i.e., single-km landing footprint)
- Mars Ascent Vehicle (MAV) (i.e., system demonstration at Earth)

- Optical communications: reduced mass/power accommodation (i.e., laboratory and field demonstration)
- Supersonic retro-propulsion (SRP) (i.e., system demonstration at Earth)
- Supersonic aerodynamic decelerators (i.e. system demonstration at Earth)

Technology investments to consider now for flight in the 2030s:

- Pinpoint landing and hazard avoidance (i.e., sub-100m landing footprint)
- *In situ* resource utilization (ISRU) (i.e., testing at relevant scales for human exploration)
- Dust effects, mitigation and toxicity
- Hypersonic aerodynamic decelerators (i.e., system demonstration at Earth)
- Higher performance solar electric propulsion, nuclear thermal propulsion, fission power systems.

In summary, numerous speakers suggested that significant program benefits would be gained through integrated SMD/HEOMD nearer-term and longer-term technology investments as part of the reformulated Mars program performed in collaboration with OCT. It was felt that these investments are enhancing for the attainment of Decadal science goals and enabling for eventual human missions to Mars. As was clear from the presentations, technology advances since the inception of the 2013-2022 Decadal Survey have significantly increased the capabilities of small to medium sized missions. In the long term, there are substantial benefits to creating scalable solutions usable for both near-term robotic and future human missions.

International Cooperation

As identified in the Decadal Survey *"Space exploration has become a worldwide venture, and international collaboration has the potential to enrich the program in ways that will benefit all participants. The program therefore relies more strongly than ever before on international participation, presenting many opportunities for collaboration with other nations. Most notably, the ambitious and complex Mars Sample Return campaign is critically dependent on a long-term and enabling collaboration with the European Space Agency (ESA)."* (Vision and Voyages, Executive Summary, p. 2) Clearly, there exists a substantial interest from the international community in the exploration of Mars. In Europe it is highly likely that a 2016 Trace Gas Orbiter and a 2018 ExoMars Rover mission with a 2-m drill will be implemented by the European Space Agency (ESA) in collaboration with the Russian Space Agency. The science results of the ExoMars rover mission, in particular the subsurface search for organics, will provide important contributions towards Mars sample return. These missions will maintain a preponderance of the original goals of the ESA-NASA collaboration. ESA is also looking at post-2018 missions and technologies in the frame of the EREP program, which maintains a strong focus on a Mars sample return mission.

As Europe strives to rebuild the ExoMars mission with Russian participation, modest US contributions to the missions, similar to that for US participation in ESA's JUICE mission, could do much to renormalize relations. In particular, completion of the MOMA instrument for inclusion in ExoMars, and the establishment of an early ExoMars US Participating Scientist program, would do much to facilitate US involvement in planning and early access to science from that mission. At a national level in Europe the competence for development of complex scientific instruments remains high, and there is significant potential for bilateral collaboration at the payload level that should be taken into account in any planning effort for future Mars missions.

In Canada the commitment to major atmospheric experiments such as the ESA-NASA 2016 MATMOS instrument remains intact. Several funded projects also contribute significantly to the development of rover mobility systems and instruments.

In summary, many speakers noted how international partnerships can be highly enabling, especially as Mars exploration missions become increasingly complex. Such partnerships may be at the mission or instrument level, and/or involve participating scientists. A strong connection with potential international partners is essential early in mission planning and must be maintained throughout mission implementation. For relatively modest cost, it was suggested that a reinvigoration of the US participation in ESA's ExoMars mission could do much to repair relations between Europe and the US in robotic planetary exploration.

Education and Public Outreach

The Workshop funded the travel for 10 university students to attend the workshop and present their concepts for Mars exploration. It is possible that other students also submitted abstracts and made presentations, as there were many young scientists and engineers at the Workshop, and additional students may not have needed travel funds. Also, 12 local middle and high-school students who have worked on robotic projects at their schools attended the meeting on Wednesday between 10 am and 1 pm to talk to scientists and engineers about their designs and the realities of Mars robotic exploration. There was a lively interaction with the workshop attendees, and several of the students requested and were encouraged to attend the afternoon Breakout Sessions.

There remains strong public support for NASA's robotic exploration of Mars. The sustained interest in activities of the MER rovers and the frequent new and exciting discoveries from orbit and on the surface have maintained a strong following in the general public and especially in middle and high-school children. The upcoming landing of the Mars Science Laboratory will be a major public relations activity for NASA and will herald a new era of exploration that will capture strong societal interest in Mars and the space program in general.

It was clear from the discussion in the Breakout Groups and in the hallways that it is important to sustain the education and outreach programs for Mars exploration and evolve them as the style of social interaction changes. Engagement and sustenance of strong public support is critical to the continued vitality of the Mars exploration program, especially as more challenging and higher pay-off missions are likely to demand higher mission costs.

Appendix *1. Participant List (by Presenter)*

Oral Presentations:

Abstract Number	Name	Affiliation	Abstract Number	Name	Affiliation
4254	M. Nurul Abedin	NASA Langley Research Center	4363	Pascal Lee	Mars Institute & SETI Institute
4202	James Abshire	NASA Goddard Space Flight Center	4276	Larry Lemke	NASA Ames Research Center
4104	Mark Allen	Jet Propulsion Laboratory / Caltech	4086	Joel Levine	College of William and Mary
4293, 4269	Farzin Amzajerdian	NASA Langley Research Center	4192	Darlene Lim	NASA Ames Research Center
4324	F. Scott Anderson	Southwest Research Institute	4078	Michael Lisano II	Jet Propulsion Laboratory
4143	Paul Backes	Jet Propulsion Laboratory	4289	Paul Lucey	University of Hawaii
4072, 4075	Yoseph Bar-Cohen	Jet Propulsion Laboratory	4135	Joseph Lukas	University of Maryland
4205	Brad Bebout	NASA Ames Research Center	4060	Michael Malin	Malin Space Science Systems
4252, 4365	Luther Beegle	Jet Propulsion Laboratory	4107	Robert Manning	Jet Propulsion Laboratory / Caltech
4188	Rohit Bhartia	Jet Propulsion Laboratory	4352, 4378	James Masciarelli	Ball Aerospace & Technologies Corp.
4224	Beau Bierhaus	Lockheed Martin Space Systems	4207	Ayako Matsuoka	Japan Aerospace Exploration Agency, JAPAN
4056	Brian Birge III	private	4326	Daniel Mazanek	NASA Langley Research Center
4309	Jordana Blacksberg	Jet Propulsion Laboratory	4322	Timothy McElrath	Jet Propulsion Laboratory / Caltech
4071	David Blake	NASA Ames Research Center	4284	Alfred McEwen	University of Arizona
4157	Joseph Bonetti	Jet Propulsion Laboratory / Caltech	4215	Michael McGee	Lockheed Martin Space Systems
4299	Nathan Bramall	Los Gatos Research	4091	Chris McKay	NASA Ames Research Center
4236, 4292	William Brinckerhoff	NASA GSFC	4152	Christopher McQuin	Jet Propulsion Lab, CalTech
4283	Shane Byrne	Lunar and Planetary Laboratory	4209	Igor Mitrofanov	Institute for Space Research, RUSSIA
4338	Morgan Cable	Jet Propulsion Laboratory	4112	Robert Moeller	Jet Propulsion Laboratory
4298	Wendy Calvin	University of Nevada - Reno	4239	Mohammad Mojarradi	Jet Propulsion Laboratory
4156	Bruce Campbell	Smithsonian Institution	4353	Greg Mungas	Firestar Technologies
4287	Charles Campbell	NASA JSC	4175	Michelle Munk	NASA Langley Research Center
4285	Lynn Carter	NASA GSFC	4203	Scott Murchie	JHU Applied Physics Laboratory
4342	Ashley Chandler	Stanford University	4262, 4296	Anthony Muscatello	NASA KSC
4201	Valerie Ciarletti	LATMOS/IPSL/UVSQ, FRANCE	4150	Charles Naudet	Jet Propulsion Laboratory
4093	Ian Clark	Jet Propulsion Laboratory	4158	Issa Nesnas	Jet Propulsion Laboratory
4312, 4346, 4385	Stephen Clifford	Lunar and Planetary Institute	4234	Paul Niles	NASA JSC
4119	Barbara Cohen	NASA MSFC	4066	Matthew North	Northwest Florida State College
4180	Anthony Colaprete	NASA Ames Research Center	4045	Danielle Nuding	University of Colorado Boulder
4058	John Connolly	NASA JSC	4054	David Oh	Jet Propulsion Laboratory
4098	Steve Creech	NASA Marshall Space Flight Center	4128	Aaron Parness	Jet Propulsion Laboratory
4306	David Cullen	Cranfield University, UNITED KINGDOM	4065	Victor Parro	Centro de Astrobiología (INTA-CSIC), SPAIN
4247	Murray Darrach	Jet Propulsion Laboratory	4279	Ann Parsons	NASA GSFC
4186	Arwen Davé	Lockheed Martin IS&GS	4344	Kurt Polzin	NASA MSFC
4238	Faranak Davoodi	Jet Propulsion Laboratory	4384	Dave Poston	Los Alamos National Laboratory
4343	Matthew Deans	NASA Ames Research Center	4177	Richard Quinn	SETI Institute
4308	Richard Dissly	Ball Aerospace	4325	Michael Ravine	Malin Space Science Systems
4016	Benjamin Donahue	Boeing	4265	Joseph Riedel	Jet Propulsion Laboratory
4220	Christian Dujarric	European Space Agency, FRANCE	4195	Sarag Saikia	Purdue University
4151	Karl Edquist	NASA Langley Research Center	4208	Gerald Sanders	NASA JSC
4228	Bethany Ehlmann	California Institute of Technology	4165	Orlando Santos	NASA - Ames Research Center
4121, 4221	Harvey Elliott	University of Michigan	4193	Daniel Scharf	Jet Propulsion Laboratory / Caltech
4381	Michael Elsperman	Boeing	4166	John Schofield	Jet Propulsion Laboratory
4328	Edwin Ethridge	NASA MSFC	4132	Dan Schumacher	NASA MSFC
4190	Wolfgang Fink	University of Arizona	4140	Piers Sellars	NASA GSFC
4179, 4181, 4187	David Folta	NASA GSFC	4275	R. Glenn Sellar	Jet Propulsion Laboratory
4349	Renee French	Northwestern University	4057	WIlliam Sellers Jr.	private
4092	Matthew Frost	Jet Propulsion Lab, Caltech	4134	Erik Semrud	University of Maryland
4160	Thomas Gemmer	North Carolina State University	4059	Csaba Singer	German Aerospace Center, GERMANY
4302	Stephanie Getty	NASA Goddard Space Flight Center	4347	Ronald Sostaric	NASA JSC
4217	Everett Gibson	NASA Johnson Space Center	4366	Jim Spann	NASA MSFC
4184, 4185	Brian Glass	NASA Ames Research Center	4307	Joel Steinkraus	Jet Propulsion Laboratory
4336	Yves Gonthier	Canadian Space Agency, CANADA	4114	Carol Stoker	NASA Ames Research Center
4074	John Grant	Smithsonian Institution	4277	Nathan Strange	Jet Propulsion Laboratory / Caltech
4204	Bob Grimm	Southwest Research Institute	4067	Brett Streetman	Draper Laboratory
4216, 4367	Rob Grover	Jet Propulsion Laboratory	4241	Theodore Sweetser	Jet Propulsion Laboratory, Caltech
4303	Frank Grunthaner	Jet Propulsion Laboratory / Caltech	4126	Shayne Swint	NASA MSFC
4138	Scott Guzewich	Johns Hopkins University	4350	James Szabo Jr	Busek Co. Inc.
4330	Michael Hecht	Jet Propulsion Laboratory / Caltech	4316	Michael Tinker	NASA Marshall Space Flight Center
4089	Hamid Hemmati	Jet Propulsion Laboratory	4167	Timothy Titus	U.S. Geological Survey
4382	Victoria Hipkin	Canadian Space Agency, CANADA	4222	Mark Trinidad	Northrop Grumman
4032, 4041	Steven Howe	Universities Space Research Association	4214	Azita Valinia	NASA GSFC
4260	Zhengwei Hu	XNano Sciences	4125	Ethiraj Venkatapathy	NASA Ames Research Center
4372	Kenneth Hurst	Jet Propulsion Laboratory	4286	Meenakshi Wadhwa	Arizona State University
4341	Andrew Johnson	Jet Propulsion Laboratory	4256	Norman Wainwright	Charles River Laboratories
4103	Charles Johnson	NASA MSFC	4339	Richard Warwick	Lockheed Martin Space Systems
4162	Johnathan Jones	NASA Langley Research Center	4229	Chris Webster	Jet Propulsion Laboratory
4176	John Karcz	NASA Ames Research Center	4291	Peter Willis	California Institute of Technology
4383	Laurel Karr	NASA MSFC	4082, 4294	Aron Wolf	Jet Propulsion Laboratory
4361	Laszlo Kestay	U.S. Geological Survey	4327	Paul Wooster	SpaceX
4235	Tom Komarek	Jet Propulsion Laboratory	4375, 4380	James Wray	Georgia Institute of Technology
4371	Kimberly Kuhlman	Planetary Science Institute	4145	Henry Wright	NASA Langley Research Center
4357	Emil Kursinski	Braod Reach Engineering	4257, 4259, 4263, 4268, 4280, 4282	Kris Zacny	Honeybee Robotics
4340	David Lawrence	JHU APL	4069	Robert Zubrin	Pioneer Astronautics
4329	Michael Lee	Jet Propulsion Laboratory			

Print Only (authors were not invited to present these abstracts at the workshop, but participants were encouraged to peruse these abstracts also):

Abstract Number	Name	Affiliation	Abstract Number	Name	Affiliation
4337	Mark Adler	Jet Propulsion Laboratory	4099	Thomas Kuiper	Caltech
4063	Carlton Allen	NASA Johnson Space Center	4233, 4237	Damon Landau	Jet Propulsion Laboratory
4105	Mark Allen	Jet Propulsion Laboratory/Caltech	4219	Geoffrey Landis	NASA John Glenn Research Center
4319	Ariel Anbar	Arizona State University	4178	Jared Lang	Jet Propulsion Laboratory
4142	Jeffrey Antol	NASA Langley Research Center	4356	Larry Lemke	NASA Ames Research Center
4288	Sami Asmar	Jet Propulsion Laboratory	4155	Amy Lo	Northrop Grumman
4030	Sayavur Bakhtiyarov	DOD Air Force	4154	Mark Lupisella	NASA GSFC
4076	Yoseph Bar-Cohen	Jet Propulsion Laboratory	4274	Bruce Mackenzie	Mars Foundation
4131	Szaniszló Bérczi	Eötvös University, HUNGARY	4025	Daniel Marcus	private
4267	Edward Bierhaus	Lockheed Martin Space Systems	4053	Geovanni Martinez	University of Costa Rica
4171	Bruce Bills	Jet Propulsion Laboratory	4379	James Masciarelli	Ball Aerospace & Technologies Corp.
4073	Jan Boom	N.C.B. Naturalis, NETHERLANDS	4153	Andrew Maxwell	Georgia Institute of Technology
4046	Ward Brullot	KU Leuven, BELBIUM	4272	Brian McConnell	Worldwide Lexicon Inc
4334	Milos Bukumira	High Graphic School, YUGOSLAVIA	4318	Timothy McElrath	Jet Propulsion Laboratory / Caltech
4196	Fred Calef III	Jet Propulsion Laboratory	4359	Philip Metzger	NASA Kennedy Space Center
4206	Carlos Calle	NASA KSC	4035	Yasunori Miura	Yamaguchi University, JAPAN
4210	Christopher Carr	MIT	4331	Rakesh Mogul	Cal Poly Pomona, SETI Institute
4095	Ian Clark	Jet Propulsion Laboratory	4050	Jahaziel Morales Mor	Yazaki Service, S de R.L. de C.V., MEXICO
4144	Larry Craig	NASA KSC	4020	Christian Muller	B.USOC, BELGIUM
4301	Ingrid Daubar	University of Arizona	4173, 4174	Michelle Munk	NASA Langley Research Center
4240, 4300	William Delamere	Delamere Space Sciences	4230, 4244, 4358	Marcus Murbach	NASA Ames Research Center
4271	Jason Denhart	North Carolina Sate University	4064	Scott Murchie	JHU Applied Physics Laboratory
4200	Carl DeSouza	Royal Melbourne Institute of Technology, AUSTRALIA	4314	Shawn Murphy	Draper Laboratory
4313	Hugh Dischinger Jr.	George C. Marshall Space Flight Center	4043	Takashi Nakamura	Physical Sciences Inc.
4332	Richard Dissly	Ball Aerospace	4218	Mark Nall	NASA
4270	Colin Dundas	U.S. Geological Survey	4113, 4115, 4116, 4118	Kent Nebergall	Day Five, LLC
4355	Stephen Edberg	Jet Propulsion Laboratory	4231	Jeffrey Osborne	International Space University, FRANCE
4333, 4360	Jennifer Edmunson	NASA MSFC/BAE Systems	4246	Alexey Pankine	Space Science Institute
4194	Lionel Ernest Edwin	North Carolina State University	4159	Jeff Plescia	JHU Applied Physics Lab
4278	Tarek El-Gaaly	Rutgers University	4106	James Pope	NASA Kennedy Space Center
4017	Thomas Elifritz	The Tsiolkovsky Group	4130	Jill Prince	NASA Langley Research Center
4090, 4137	John Elliott	Jet Propulsion Laboratory	4249	Richard Quinn	SETI Institute
4168	Dean Eppler	NASA JSC	4147	William Ray	NthDegree Technologies Worldwide LLC
4317	Thomas Eubanks	LiftPort	4198, 4345	Nilton Renno	University of Michigan
4304	Jack Farmer	Arizona State University	4102	Antonio Ricco	NASA Ames Research Center
4368	Miranda Fateri	Fachhochschule Aachen, GERMANY	4087, 4088	Glen Robertson	NASA MSFC
4163	Martin Feather	Jet Propulsion Laboratory / Caltech	4297	Monsi Roman	NASA MSFC
4164	Robin Fergason	US Geological Survey	4161	Daniel Scharf	Jet Propulsion Laboratory / Caltech
4248	Erik Fischer	University of Michigan	4255	Jill Scott	Idaho National Laboratory
4264	William Fletcher	NASA MSFC	4320	Douglas Sheldon	Jet Propulsion Laboratory
4084	Martin Frettloeh	Anvium, GERMANY	4068, 4213	Brent Sherwood	Jet Propulsion Laboratory
4273	Raymond Gilstrap	NASA Ames Research Center	4042	Fred Singer	private
4251, 4253	Yonggyu Gim	Jet Propulsion Laboratory	4295	Alberto Soto	National Autonomous University of Mexico, MEXICO
4226	Lee Graham	NASA Johnson Space Center	4123	Robert Staehle	Jet Propulsion Laboratory
4323	Steven Greybush	The University of Maryland	4033	Andreas Stuermer	University of Applied Sciences, AUSTRIA
4364	Robert Grimm	Southwest Research Institute	4242	Theodore Sweetser	Jet Propulsion Laboratory / Caltech
4311	Douglas Halleaux	University of Michigan	4108	Kenneth Tanaka	U.S. Geological Survey
4061	William Halliday	International Union of Speleology	4169	Richard Terrile	Jet Propulsion Laboratory / Caltech
4097	Charles Halsell	Jet Propulsion Laboratory	4120	James Tickner	CSIRO, AUSTRALIA
4369	Emmanuel Hanna	Caltech	4227	Harold Trammell	University of Houston
4335, 4354	Michael Hecht	Caltech	4077	Ashitey Trebi-Ollennu	Jet Propulsion Laboratory / Caltech
4055	Daniel Hernandez	Devil-Hop, FRANCE	4348	Huu Trinh	NASA MSFC
4031, 4034	Steven Howe	Universities Space Research Association	4281	Friso HW van Amerom	SRI International
4109	James Jordan	Jet Propulsion Laboratory	4048	Vandendriessche	KU Leuven, BELGIUM
4111	James Jordan	Jet Propulsion Laboratory	4149	Ethiraj Venkatapathy	NASA Ames Research Center
4315	John Karcz	NASA Ames Research Center	4141, 4197	Martin Voelker	Freie Universität Berlin, GERMANY
4083	Suniti Karunatillake	Rider University	4182	Kevin Wallace	NASA MSFC
4110	Sharon Kedar	Jet Propulsion Laboratory	4146	James Wertz	private
4225	Brett Kennedy	Jet Propulsion Laboratory	4290	John Whitehead	private
4232, 4351	Laszlo Kestay	U.S. Geological Survey	4191	David Willson	NASA Ames Research Center
4094	Soon Sam Kim	Jet Propulsion Laboratory	4310	Ernest Wyatt	Jet Propulsion Laboratory
4081	Kerry Klein	Jet Propulsion Laboratory	4362	Samuel Ximenes	Exploration Architecture Corp (XArc)
4124	Andrew Klesh	Jet Propulsion Laboratory	4250	Cody Youngbull	Arizona State University
4245	Samuel Kounaves	Tufts University	4101	Robert Zubrin	Pioneer Astronautics

Appendix 2. Community Consensus Documents for the Robotic and Human Exploration of Mars

2013-2022 Planetary Science Decadal Survey

In March, 2011, the National Research Council of the National Academies released *Vision and Voyages for Planetary Science in the Decade 2013-2022* (the Planetary Science Decadal Survey). This report was prepared by the Committee on the Planetary Science Decadal Survey, which was composed of members of the scientific community. A Steering Group of the Committee provided oversight of the process and developed consensus findings across the various constituencies, which were represented by the Inner Planets Panel, the Mars Panel, the Giant Planets Panel, the Satellites Panel, and the Primitive Bodies Panel. Each Panel was represented on the Steering Group, and prepared a chapter in the Survey. Inputs in the deliberations of the Panels and Steering Group were provided by representatives of stakeholder groups, and through the submission of White Papers.

The Planetary Decadal made the following recommendations:

- Small missions – the Discovery program should continue, with frequent opportunities (≤24 months), and a cost cap per mission of $500 million in FY2015 dollars. These missions are PI-led and are not pre-defined by the Decadal.
- Mars Trace Gas Orbiter – while a small mission outside the Discovery Program, this ESA-NASA mission set for launch in 2016 should be supported *"as long as the currently negotiated division of responsibilities and costs with ESA is preserved."*
- Medium missions – two New Frontiers missions should be selected in the coming decade with a cost cap of $1.0 billion in FY2015 dollars. While a suite of missions was identified as potential opportunities in the coming decade, no Mars missions were identified in this mission class.
- Large missions – the highest priority flagship mission for the decade is the Mars Astrobiology Explorer – Cacher (MAX-C), the first in a three-mission ESA-NASA Mars Sample Return campaign. It was recommended that this mission should only be flown is the total cost to NASA does not exceed $2.5 billion in FY2015 dollars.
- Balance – the committee recommended *"a balanced mix of small Discovery missions, medium-size New Frontiers missions, and large "flagship" missions, enabling both a steady stream of new discoveries and the capability to address major challenges."*
- NASA-funded supporting R&A and Technology – the research and analysis budget for planetary science should increase by 5% in 2013 and increase annually by 1.5% above inflation; the technology budget for planetary science should be 6-8% of the total Planetary Science Division budget.
- If less funding is available than assumed by the Decadal Survey, the first step should be to descope or delay (but not cancel) flagship missions, followed by slipping New Frontiers and/or Discovery missions if adjustments to flagship missions cannot solve the problem. A high priority is placed on preserving R&A and technology development funding.

Mars Exploration Program Analysis Group (MEPAG) Science Goals, Objectives, Investigations, and Priorities: 2010

MEPAG is a community-based group that provides findings to NASA pertaining to activities associated with the exploration of Mars by robotic and eventually human missions. In this role, MEPAG maintains a Science Goals, Objectives, Investigations, and Priorities document that is periodically updated to reflect the current state of knowledge and evolving priorities associated with Mars exploration. The latest version of this report dates from 2010 and has the following unprioritized Goals and supporting prioritized Objectives:

- Goal I: Determine if life ever arose on Mars (Life)
    - Objective A: Characterize past habitability and search for evidence of ancient life
    - Objective B: Characterize present habitability and search for evidence of extant life
    - Objective C: Determine how the long-term evolution of Mars affected the physical and chemical environment critical to habitability and the possible emergence of life
- Goal II: Understanding the processes and history of climate on Mars (Climate)
    - Objective A: Characterize Mars' atmosphere, present climate, and climate processes under current orbital configuration
    - Objective B: Characterize Mars' recent climate and climate processes under different orbital configurations
    - Objective C: Characterize Mars' ancient climate and climate processes
- Goal III: Determine the evolution of the surface and interior of Mars (Geology)
    - Objective A: Determine the nature and evolution of the geologic processes that have created and modified the Martian crust
    - Objective B: Characterize the structure, composition, dynamics, and evolution of Mars' interior
    - Objective C: Understand the origin, evolution, composition and structure of Phobos and Deimos
- Goal IV: Prepare for human exploration
    - Objective A: Obtain knowledge of Mars sufficient to design and implement a human mission with acceptable cost, risk and performance

In their White Paper to the Decadal Survey, MEPAG made the recommendations:

"The following mission building blocks are proposed for the coming decade:

- *TGM to determine the abundances and spatial/temporal variations of trace gases and isotopes in the present atmosphere and their implications for life*
- *NET to explore the nature and history of the interior and the implications for the surface and atmospheric environments*
- *MSR [MAX-C + Return Lander & Orbiter] to return diverse suites of carefully chosen samples from a well-characterized site to Earth for detailed geological and astrobiological study.*

These steps would make the greatest progress to answering fundamental questions of Solar System science, including the age-old question of whether Mars is today—or ever was—an abode of life."

Precursor Strategy Analysis Group

This Group, jointly sponsored by the MEPAG and the Small Bodies Assessment Group (SBAG), was charged in early 2012 with providing an analysis of Strategic Knowledge Gaps (SKGs) associated with potential human missions to the Mars System. SKGs were identified associated with the first human mission to Mars orbit, the first human mission to land on either Phobos or Deimos, the first human mission to the Martian surface, and sustained human presence on Mars. The group made the following findings:

1. The high-priority gaps for a human mission to Martian orbit relate to a) atmospheric data and models for evaluation of aerocapture, and b) technology demonstrations.
2. A human mission to the Phobos/Deimos surface would require a (robotic) precursor mission that would land on one or both moons.
3. The early robotic precursor program needed to support a human mission to the Martian surface would consist of at least:
    - One orbiter
    - A surface sample return (the first mission element of which would need to be a sample-caching rover)
    - A lander/rover-based *in situ* set of measurements (which could be made from the sample-caching rover)
    - Certain technology demonstrations
4. P-SAG has not evaluated whether it is required to send a lander or rover to the actual human landing site before humans arrive.
5. For several of the SKGs, simultaneous observations from orbit and the Martian surface need to be made. This requires multi-mission planning.
6. There are five particularly important areas of overlap between HEO and science objectives (in these areas, mission concepts with dual purpose would be possible)
    1. Mars: Seeking the signs of past life.
    2. Mars: Seeking the signs of present life.
    3. Mars: Atmospheric dynamics, weather, dust climatology.
    4. Mars: Surface geology/chemistry.
    5. Phobos/Deimos: General exploration of Phobos/Deimos.

Technology and Enabling Capabilities

Panel Summary by
Michael Amato
Bethany Ehlmann
Vicky Hamilton
Brian Mulac

June 12-14, 2012

I. Fixed Landers & Communication— Summary

- 3 main concepts for delivery platforms. First two drawn on heritage, last is low cost, high risk
  - Proven in Prior Mission (Phoenix, MER): reduce development cost, focus on payload development
  - Dragon commercial platform : potential for lower cost delivery of large payload; possible interest from human exploration?; technology hurdles, in particular, proof of deep-throttling, supersonic retro propulsion, science accomodation.
  - "Piggybacking"/ Multiple small landers: low cost permits higher risk, redundancy, multiple surface data points, e.g. related to weather/climate, greater community/student involvement; better to fly these than ballast!
- Recurring theme of drill or mini-corer for sampling subsurface ice/soil to address science objectives. Drills prototyped and tested.
- Only communication presentation was laser comm: would greatly enhance science data volumes, advancements made, still needs to address technological challenges for Mars
- Science interest in modern climate/life and processes and enabling technologies, complementary to and/or precursors to MSR
  - Ice exploration: ages, processes, habitability , with multiple possible approaches, e.g. roving across layers in the polar cap or coring at near-polar latitudes
  - In-situ life detection in the near subsurface
  - weather stations either stand-alone or piggybacked

II. Mobile Surface Spacecraft and Navigation—Summary

- Complexity or simplicity can both achieve autonomy in mobility
  - "thinking rover" with on-board target selection, terrain relative navigation vs. "survey mode" design of free-moving tumbleweeds
- Small is beautiful: emphasis on creative mass-lowering capabilities
  - Mini rovers, cold-capable rovers
- Major advances in access to previously unaccessible/challenging terrains (cliffs, lava tubes) using novel systems
  - Variety of methods: six legs/wheels, gripping rovers, tethered rovers, hopping
- Most technologies are being validated/have been demonstrated by testing in analog environments
- The Canadian Space Agency is testing multiple potential contributions (instruments, samplers, rovers)
- Utilizing a MER-based rover, high-level science capabilities possible on Mars surface at the 2018 reference landing sites, including organics detection and in-situ age dating

------

- Validating small tech demo system, ala Pathfinder, or ISRU for a hopper?

III. Aerial Platforms & Investigations–Summary

- Variability in maturity of design
  - A few balloon and deployed airplane/drones are currently relatively mature with mid to high TRL and have been proposed and/or gone through Phase A.
  - More advanced options (e.g., vertical landing and takeoff systems, entomopters, *in situ* CO_2 'gas hoppers' and aerocoasters) have unique access capabilities and may be options for longer term Mars pathway needs
- Mission design exerts strong control over time aloft/mission duration
- Can be on the lower end of mission and subsystem cost ranges
- Fill unique niche for coverage and access: birds-eye view good for study of regional phenomena (between global scale orbiter and local lander) and some areas presently inaccessible to current EDL systems
  - Science enabled: atmospheric gas composition, structure, winds; surface remote sensing (radar, GPR, higher spatial res. surface imaging, composition)
  - New spatial scale of vision/perspective for exploration
  - Possible synergy with MSR and human missions, i.e. balloon for near real-time assessment of local winds before launch
- Some aerial systems can be subsystems deployed from larger missions; others could be co-manifested with other missions

IV. Sample Caching, Handling, Acquisition –Summary

- A number of well-tested concepts for drilling and/or caching
  - Two coring concepts for MSR (10mm diameter x ~50-80mm)
  - Previewable within cached bits and/or encapsulated within cachable tubes
- Deeper drills to access subsurface, including ices
  - Geared toward in-situ analysis with wet chemistry; could also cache a sample
- Relatively small platforms enable these activities
  - Phoenix: meter to few meter drill
  - MER: sample acquisition and caching + science payload
- Characterization needed and instruments under development for sampling and sub-sampling, e.g.,
  - In-situ, non-destructive organics (incl. deep UV)
  - In-situ, non-destructive mineralogy (e.g. spectroscopy, next-gen. XRD)
  - "scratch and sniff" for analysis of presence of trace organics prior to triage
  - Precision subsampling of core systems under developments
- Avoiding contamination
  - Encapsulation in tubes at drilling
  - Air gaps
  - Bioshielding
- Development/interest in microfluidics systems for in-situ wet chem.
- CubeSat-like architecture for Mars orbit-to-Earth orbit transfer of sample

V. Return Architectures Strategies, Vehicles–Summary

- MAVs
  - Functional technology is not new; application to Mars environment pose challenges
  - Challenges: Mars surface temperature change, stage separation, achieving orbit, packaging
  - Need for Earth (and Mars?) demonstrations of feasibility
- Solar-electric-propulsion tugs and on-orbit staging were presented as long-term options for greater mass or delta-V interplanetary transport capabilities
- Heavy launch capabilities (SLS) first tests in 2017, are robotic mission uses later?
- Earth-return capsule: initial findings/status presented for in inverted spherical cone and no parachute design
- Architecture option #1: Upper atmosphere, dust sample return, no rendezvous-Earth-return
  - mature (proposed to Discovery)
- Architecture option #2a: MER+MAV and #2b: Phoenix lander+MAV (both w/ and w/o no rendezvous Earth-return)
  - Variable levels of maturity
  - Regolith (upper 10 cm depth), rock chip, atmosphere sample
- Architecture option #3a: caching MER, part 1 of multi-step architecture and #3b precursor exploring rovers
  - Returns rock cores collected in stratigraphic context
- Discussion of pushback on planetary protection driving requirements for all types of samples and related potential mission impacts

Themes - A number of concepts make use of heritage-based platforms that are plausible

- Spread between the 5 sessions were a number of presentations (~7 or 8) using or referencing a MER class platform for missions, primarily sample acquisition and interrogation missions:
  - A number of those presentations on the readiness of core-based sample acquisition and caching systems intended specifically for MER class rover missions.
  - Several instrument presentations focus on either sample triage, enabling selection, aiming for fitting on MER platform
  - Two non-sample-return based MER based rover missions on Ice sample acquisition, MSR precursor is situ life detection suites, age dating, polar science
  - MER based or MER class rover missions that could cache samples or do science/Strategic Knowledge Gaps/pre-MSR science appear to be possible ‘nearer’ term. Modifications or updates probably needed for MER class EDL and rover were noted
  - One carries MAV for sample return

- Approximately ten presentations reference Phoenix based fixed lander missions:
  - A number were on deep drilling (1-3m) into ice or soil and MSR precursor science, also related to atmospheric measurements
  - A number focused on varying degrees of MSR with atmosphere, regolith, rock chip samples
  - Some carry MAVS, less mature
  - Fixed lander mission approaches and technologies discussed can do some pre MSR science and Strategic Knowledge Gaps and can obtain and analyze or cache samples.

- Multiple Aerial drone or balloon missions:
  - Pre MSR science for atmosphere and surface regional studies

- Longer term :
  - Extreme terrain mobility and other ‘mobility’ solutions could be available for mid to later pathways if science, human mission related knowledge gaps needs or human orbit or surface operations would benefit.
  - There are innovative ideas – for example - Dragon based EDL and fixed landers could provide science platforms and mature potential subsystems for human missions, but they may need work.
  - MAV technologies a risk for most sample return scenarios of any cost range.

Science and Mission Concepts:

Panel Summary by
Doug Stetson
Steve Clifford
Jorge Vago

June 12-14, 2012

Science and Mission Concepts

Topic Areas

- Using Mars Moons
  - Rationale and mission concepts
- Motivating Science
  - Identification and exploration of modern aqueous/icy environments
  - Strategic investments and imperatives
- Compositional Investigations
  - New and improved sensors and instruments
- Geophysical Investigations
  - Subsurface exploration techniques
  - Martian interior
- Organic Molecule and Life Detection
  - Measurement strategies
  - Sensors and instruments

Cross-Cutting Themes

- Enhancing the value of Mars Sample Return: Site and sample selection
- Preparing for human exploration: Precursors, locations, resources
- Ensuring human safety and productivity
- Unlocking the mysteries of Mars: New opportunities for the next decade

Enhancing MSR

- Our understanding of Mars, especially evidence for an active hydrologic cycle, has advanced significantly even since the Decadal Survey
  - Possible/likely present-day water and brines (gully processes/RSLs)
  - Amount and distribution of ice, esp. mid-latitude ice
  - Geology/geomorphology indicative of past water and habitable environments
- There are significant investigations that could/should be done prior to committing to a specific MSR site and mission architecture
  - Imaging radar and and atmospheric composition to localize interesting sites
  - Detailed imaging and compositional mapping from orbit
  - In situ exploration of diverse sites (surface and subsurface)
  - GPR for geological context and detection of ice/habitable environments
  - Detailed chemical/biological analysis to fine-tune sites and sample selection
- Ensuring the scientific success and operational safety of MSR
  - In situ sample assessment: Micro-imaging, mineralogy, wet chemistry
  - Sample caching and monitoring: Smart containers
  - High-resolution mapping of specific sites

Preparing for Human Exploration

- Continued scientific study of Mars is a key to enabling targeted, cost-effective human exploration
  - Extensive characterization of environments (surface/subsurface)
  - High-resolution mapping of mineralogy, resources – site selection
  - Subsurface sounding and imaging radar
  - Bioassays
  - Polar locations are scientifically compelling and potentially resource-rich human destinations, and merit further study
- Understanding the subsurface is an important step (resources/habitability)
- Phobos/Deimos are important destinations that may provide much of the value of human surface exploration at reduced cost and risk
  - Natural space stations and a potential "base camp"
  - Teleoperation of surface payloads and habitat build-up; alleviates some planetary protection issues
  - Accessible resources
  - Compositional studies, and possibly sample return, are critical robotic precursors

Ensuring Human Safety and Productivity

- Robotic science missions will provide critical knowledge for safe and effective human exploration
  - New sensor and instrument concepts hold the promise of providing significant new data at relatively low cost
  - Characterization of atmosphere and landing sites, and correlation of orbital and in situ data
  - High-resolution imaging and detailed topographical maps
  - Understanding toxicity ("some Mars locations would be Superfund sites")
- Evolution of robotic science instruments will lead to devices that allow humans to conduct effective science on Mars, *for example:*
  - "Chemical laptop" for rapid assessment of biological activity or potential
  - Backpack GPR to determine drilling sites
  - "Tricorder" for sample selection – interior of rocks with minimal preparation
- Exploit terrestrial analogs to establish a culture of field work
- Enhance systems engineering approach – requirements flowdown from human needs to robotic/science missions and measurements

Unlocking the Mysteries of Mars: Fundamental Planetary Science

There is a tremendous amount of important planetary science to do at Mars, independent of MSR and human exploration

- Exploration of unique environments to understand planetary evolution and habitability
- Martian interior through seismic studies
- Climate evolution and atmospheric processes/escape
- Search for past and present life
  - Diverse suite of sensors and techniques to detect and characterize biological activity and potential
  - Broad approach recommended: Surface and atmosphere from orbit, in situ sample analysis (chemical and morphological), subsurface
- Phobos and Deimos – origin and composition

A reformulated Mars program should preserve these important aspects of the overall solar system exploration program

Key Issues and Recommendations

- Readiness for Mars Sample Return
  - New findings since Decadal should be considered during program reformulation
  - Value of MSR would be enhanced by further robotic missions
  - Need to factor in results from MSL and ExoMars, especially in regards to habitability and subsurface
  - New life detection concepts hold great potential to enhance understanding prior to MSR and could lead to optimum mission architecture
- Near-term opportunities
  - 2018/2020 opportunities should be considered for site/atmosphere characterization from orbit, and lander/small rover to specific interesting locations
- Internationalize MSR and restore some (limited) participation on ExoMars
- Re-establish a regular means to conduct small focused Mars missions
- Ensure a well-funded R&A program including studies of martian meteorites and development of sample analysis techniques

Human Exploration and Precursors

Panel Summary by
John Connolly
Chris McKay
John Karcz

June 12-14, 2012

Tuesday 10:00 am
Human Exploration and Precursors:
In-Situ Resource Utilization

- Incorporating ISRU into human or robotic missions requires a shift in mindset
  - Current: "Everything you need is launched with you from Earth"
  - Proposed: "You don't need to bring everything with you. Resources exist at your destination that can be extracted and used".
- ISRU and MSR are a natural fit. ISRU will significantly reduce the launch and entry mass of a MSR mission, and may enable new mission modes (such as direct return) not possible with current technologies
- Human systems, including ISRU, need to be tested at relevant scales prior to being used in the critical path of human missions
- Link human and robotic exploration strategies as early as possible
- New ISRU products, which offer new mission possibilities and alternatives, are under study:
  - Methane
  - Magnesium
  - Perchlorates
  - Sulfur
- ISRU is loved by some, and misunderstood or feared by others
- ISRU based missions (such as direct return MSR) need to be studied at a true mission design level to understand them in more than a parametric way

Tuesday 2:00 pm
Human Exploration and Precursors:
Power and Propulsion

- The robotic and human exploration programs should increase collaboration of Power and Propulsion systems
- Solar Electric Propulsion may expand the options available for near-term MSR missions (for Earth-Mars and Mars-Earth transit)
- Further investigation is warranted on recent propulsion technologies (Pulsed Inductive Thruster, Micro Electro Fluidic Spray)
- Interest in systems that scale from near term robotic mission to human scale
- NTP is currently judged to more compatible with human Mars missions than EP (high thrust, reduced trip time)
  - SEP/NEP is an option, but further challenges human research technology
  - NTP will enable very large scale planetary science missions (JIMO example)
- New small nuclear concepts, potentially valuable for surface scientific mission
- Fission power systems will be needed for human Mars surface missions

Wednesday 8 am
Human Exploration and Precursors:
Humans on or Near Mars

Key points of agreement

1. There are new technologies for controlling dust accumulation.
2. There are new, highly capable instruments for measuring radiation in-situ
3. Novel ideas for ISRU for construction based on core-drilled bricks
4. New highly capable instruments for biomarker assay.
5. Both MSR and human Mars missions comprise a RANGE of missions and activities, and should not be treated as point milestones

Key Discussion : What is the suitable role for humans in the exploration of Mars?

- Teleoperation from Earth using emerging technologies (by the time we get to Mars, we will no longer need to go)
- Teleoperation from Mars orbit either in orbit or on Phobos
- On the surface of Mars and teleoperation to other locations
- No resolution

Wednesday 1 pm
Human Exploration and Precursors:
Meteorological and Atmospheric Investigations

- Beyond scientific interest, important for both robotic and human entry, descent, and landing. Majority of EDL errors arise from atmospheric uncertainty.
- Different aspects important for each—low altitude conditions (winds, density, etc.) relevant to small payloads under parachutes; mid–high altitude density important for high ballistic coefficient human-scale vehicles
- Desire for global measurements
- Continuous orbital information available for over a decade; concern about continuing that record
- Mature, low-cost, (a.k.a. feasible) concepts for orbital and surface-network measurements
- Want to understand drivers—dust, clouds, etc.—and transport
- Highly-capable surface met station network concepts viable as small secondary payloads; climate modeling community would prefer several (e.g. eight to twelve) locations across the surface

Thursday 8 am
Human Exploration and Precursors:
Entry, Descent and Landing

Key Points of Agreement

- Desire to improve and expand current EDL capabilities and technologies
- We should be pursing entry, descent, and landing concepts that can scale up from current robotic scales to large human landers.
  - TRN – no scaling, use the same system
  - HD – scalable by lander footprint
  - SRP – (no consensus, more work required)
  - Rigid decelerators (TBD)
  - Flexible decelerators (TBD)
  - Parachutes do not scale to human-class Mars missions
- There is a diverse set of entry and descent options relevant to human missions (e.g. multiple types of deployable accelerators, mid-L/D vehicles, supersonic retro-propulsion, navigation and control options), and we need to explore that space through analysis and testing, including flight testing.
- The scalable options are valuable for robotic missions, too, aiding in fully exploiting current launch options, and should be factored into near-term robotic landers.
- Specifically, terrain relative navigation and hazard avoidance are within reach for a near-term mission for little additional expense, are very valuable for both human and robotic missions, and should be pursued
- Transitions between entry systems constitute a significant risk
- Mars EDL technologies can benefit other science missions (e.g., Venus entry)
- Robotic and human exploration benefits from advanced EDL technologies – OCT should view both communities as primary customers