MEPAG

Report from the Next Orbiter Science Analysis Group (NEX-SAG)

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Table of Contents

Executive Summary

This is the final report of the Mars Exploration Program Analysis Group (MEPAG) Science Analysis Group (SAG) that was formed at the request of NASA to analyze possible science objectives and their synergies with other components of a multi-function next-generation Mars Orbiter. If approved, this orbiter could be launched as early as 2022. Through telecons, one face-to-face meeting, and discussions with experts in and out of appropriate HEOMD and SMD working groups, NEX-SAG finds the following:

A Mars Orbiter, utilizing Solar Electric Propulsion (SEP) and advanced telecom in a 5-year mission in low Mars orbit, could provide exciting new science and resource identification in addition to other programmatic functions. Such a multi-function mission should be launched in 2022 with the following goals:

- Replenish and advance the telecommunications and reconnaissance capability. Launched in 2022, this orbiter could back-up aging relay capabilities for a 2020 Mars rover in extended mission and for future spacecraft missions, whether for sample return or in preparation for exploration by humans at Mars.
- Demonstrate progress in Mars orbit towards potential sample return, via release, rendezvous, and capture of a simulated orbiting container, or—if possible—the actual return of an orbiting sample cache to Earth vicinity. Mars sample return is the *NRC Planetary Science Decadal Survey's* highest priority for flagship missions, and actual capture and return of an orbiting sample cache would be a major achievement for NASA and its industrial and international partners.
- Conduct new science investigations motivated by discoveries made since the *NRC Planetary Science Decadal Survey* published in 2011, consistent with high priority questions of that Decadal Survey and the recently updated MEPAG goals. The compelling science objectives (S-#) are:
  - S-A. Map and quantify shallow ground ice deposits across Mars together with shallow layering of water and CO_2 ices at the poles to better understand the global water inventory and atmospheric exchange today, and how ground ice records climate change on geologically younger Mars (e.g., over obliquity variation cycles);
  - S-B. Detect and characterize areas of possible present-day liquid water flow (recurring slope lineae: RSL) and link these observations with ground ice, temperature, surface composition (e.g., salts) and atmospheric properties to understand the distribution and potential for habitability of these volatile reservoirs;
  - S-C. Measure winds and characterize transport and other dynamic processes to understand current climate, water, and dust cycles, with extrapolation to past climates;
  - S-D. Characterize the occurrence and timing of major environmental transitions recorded in compositional stratigraphic records, such as discrete hydrated mineral assemblages and sedimentary bedding;
  - S-E. Carry out high-value, close-approach investigations of Phobos and Deimos.

- Find resources on Mars for future missions, especially in support of human surface exploration, and address Strategic Knowledge Gaps (SKGs). The key resource is water, which could make significant contributions to sustainable exploration when used in such diverse applications as life support, surface construction, and propellants for surface operations and ascent from Mars. Materials for civil engineering purposes are also of interest. Thus, locating the following resources are identified as orbiter Resource/SKG objectives (RS-#):
  - RS-A. Find and quantify the extent of shallow ground ice within a few meters of the surface and characterize its ice-free overburden;
  - RS-B. Identify deposits with hydrated minerals as a water resource, and potential contaminants within these deposits;
  - RS-C. Identify site-specific mineral resources and geotechnical properties.

  Pursuit of the above resource prospecting and science objectives could also fill key Strategic Knowledge Gaps (SKGs) that have high priority for human exploration, leading to two more resource/SKG objectives (RS-#):
  - RS-D. Extend the atmospheric climatology with diurnal coverage and wind measurements;
  - RS-E. (SEP only) Address gravity and surface characteristic SKGs for the Martian moons.

NEX-SAG finds a high degree of overlap between the science goals identified and the human exploration resource prospecting interests and derived objectives. The considerable synergy between requested functions enables selection of instruments that may individually address multiple science, resource/SKG, and reconnaissance needs, thereby providing a more cost effective way to achieve the full set of objectives.

Given the above resource/SKG and science objectives, NEX-SAG identified measurement capabilities or approaches needed to address them. It then identified, at a high level, proof-of-concept measurement techniques mature enough for development of an orbiter for launch in 2022. These proof-of-concept instrument types are:

- Visible imaging of HiRISE-class (30 cm/pixel) or better (~10-15 cm/pixel);
- Polarimetric radar imaging with penetration depth of a few (<10) meters and spatial resolution of ~15 m/pixel to detect ices and brines; a radar sounding mode would aid characterization of the overburden mantling a subsurface ice layer;
- Short-wave IR mapping with a spatial resolution of ~6 m/pixel with sufficient spectral resolution to detect key primary and secondary minerals, salts, and ices;
- Long-wave atmospheric sounding for wind, temperature, & water-vapor profiles;
- Thermal IR sounding for aerosol profiles;
- Multi-band thermal IR mapping of thermophysical surface properties (e.g., ice overburden and thermal inertia) and surface composition;
- Global, km-scale, wide-angle imaging to monitor weather, dust storms, and surface frosts.

Other instrument types may be applicable and may appear in preparation for, or in response to, an openly competitive Announcement of Opportunity.

NEX-SAG assessed these conceptual measurement capabilities described within the range of spacecraft being studied, from a MRO/MAVEN chemical propulsion derivative to spacecraft powered by commercially available or advanced Solar Electric Propulsion.

Such an ambitious multi-function orbiter mission, with telecommunications, reconnaissance, science and resource prospecting objectives, appears feasible only with advanced telecommunications capability and the first-time use of SEP for a Mars mission.

- Advanced telecommunication capabilities are needed to support high-resolution instruments while achieving acceptable spatial coverage. Such a telecom system would easily accommodate data returned by surface missions.
- The use of SEP for Mars missions is transformative, opening up new possibilities for improved, novel, and collaborative measurement capabilities in pursuit of the mission objectives, which include:
    - Bringing significantly more payload mass and power to low Mars orbit, which is needed to address the multiple functions and objectives of this orbiter.
    - The possibility of actually returning an orbiting sample container/cache to Earth vicinity at the end of a mission in low Mars orbit.
    - Supporting additional science investigations and technology demonstrations, including daughtercraft, if this can be done without impacting the main objectives.
    - Enabling successive campaigns through the ability to vary orbital parameters; e.g., gaining representative local time coverage from an inclined orbit and then polar coverage in a sun-synchronous orbit.
    - Enabling observations of the Martian moons during fly-bys as the orbiter spirals in closer to Mars.

A multi-purpose, SEP-powered, orbital mission as described here could make major advances in our scientific understanding of Mars and its evolution, while providing reliable telecommunications, reconnaissance, and resource location for future human and robotic missions on Mars.

The crucial discriminator between what can and should be flown is the funding available and the objectives of the funding directorates. Cross-directorate support is appropriate and crucial for the multiple objectives envisioned here.

In addition, NEX-SAG notes that international partners could provide several of the instrument types and spacecraft subsystems needed to achieve the objectives of this multi-faceted mission. Such partnering could also set in motion collaborations needed for the longer-term exploration of Mars by humans operating on its surface.

Introduction

Background

NASA Headquarters is considering flight in the early 2020's of an orbiter with the following functions:

- Replenishment of the telecommunications and reconnaissance infrastructure presently provided by Mars Odyssey and Mars Reconnaissance Orbiter.
- Scientific and technical progress on the NRC Planetary Science Decadal Survey priorities (including possible sample return) and/or follow up on new discoveries.
- Location and quantification of *in situ* resources for utilization by future robotic and human surface-based missions (i.e., resource prospecting).
- Acquisition of data to address Strategic Knowledge Gaps (SKGs) to aid exploration of Mars by human missions.

The Mars Exploration Program Analysis Group (MEPAG) Next Orbiter Science Analysis Group (NEX-SAG) was formed at the request of both the NASA Science Mission Directorate (SMD) and the Human Exploration & Operations Mission Directorate (HEOMD) to analyze possible science objectives of such a multi-function Mars orbiter and their synergies with other mission elements. The missions to follow this proposed orbiter are not yet defined, but information from this orbiter is intended to support both robotic and human exploration missions in the future.

The specific directives and requested tasks for the NEX-SAG are given in its Charter (Appendix 1). Key directives for NEX-SAG are repeated here in abbreviated form:

a) A required capability is telecommunications adequate to provide relay of commands to, and data from, landed assets and to record essential engineering data during critical events. As directed, NEX-SAG assumed that the relay and direct to Earth telecommunications capability would be at least as capable as MRO.

b) The next orbiter, potentially launched in 2022 or 2024, would carry the remote sensing capability essential to certifying landing site safety for future landed missions, including human missions. NEX-SAG was to review what capabilities that entailed.

c) NEX-SAG was to consider input from working groups of the Human Exploration Operations and Science Mission Directorates (HEOMD & SMD) chartered by NASA Headquarters. In particular, definition of the resource needs for future missions was provided by other working groups.

d) An orbiter operational lifetime of at least 5 years in Mars orbit was assumed.

e) Assessments of science objectives and priorities assumed that the InSight, ExoMars Trace Gas Orbiter (TGO), and 2020 Mars rover missions would be successful.

f) A range of spacecraft options, from a MAVEN/MRO class to more capable spacecraft were considered.

Additionally, the Mars Exploration Program directed JPL to form an Orbiter Study Team to assess various technical options for a 2022 Orbiter and to work with NEX-SAG regarding potential mission capabilities (item *f* above). Launch vehicles were directed to be in the Falcon 9/Atlas V class. Key advances being considered are advanced telecommunications systems and the first-time use for Mars of Solar Electric Propulsion (SEP), which has the potential to provide fuel-friendly orbit changes and enhanced power and mass for payloads in orbit around Mars. The Orbiter Study Team also included advanced SEP and optical communications developments by STMD and SCAN (all acronyms are listed in Appendix 5).

Procedure

NEX-SAG membership is given on page i. The NEX-SAG membership included a range of expertise suited to evaluating possible science objectives and resource prospecting needs, as well as measurement objectives and approaches to achieving them via remote sensing from orbit. After preliminary identification of major science themes, three subgroups were formed to delve into greater detail in key focus areas:

- *Ice & Polar Science*, including surface and subsurface ice.
- *Geology and Geophysics*, including modern surface processes and the preserved ancient geologic record.
- *Atmosphere-Surface*, emphasizing atmospheric transport and dynamic processes, including volatile redistribution and the interactions between the atmosphere and surface.

Other subgroups were formed as-needed to explore special issues such as:

- Approaches to filling *strategic knowledge gaps* (SKGs), as prioritized by HEOMD and within MEPAG Goal IV (MEPAG, 2015);
- Gains to be achieved with *higher resolution imaging* than that presently required for surface reconnaissance (currently 30 cm/pixel);
- Potential roles for *daughter spacecraft*; i.e., small spacecraft or probes carried into and the Mars system and then deployed;
- Possible contributions by an SEP-enabled mission to low-Mars orbit to the *exploration of Deimos and Phobos*, the moons of Mars.

Over a 6-month period, the subgroups met frequently by telecon. A weekly “all-hands” telecon included reports by the subgroups and from speakers on more general material (e.g., overviews of the revised MEPAG goals, new missions to Mars such as the ExoMars TGO and UAE Mars Mission). Via these telecons and emails, they invited and interacted with external Subject Matter Experts on various topics, typically regarding measurement capabilities and their application to the science and resource goals, but also addressing on occasion the goals themselves. A single face-to-face meeting was held in July, during which a critical mapping of science objectives to measurement objectives, and then to proof-of-concept measurement (instrument proof-of-concept) approaches, was begun. The Orbiter Study Team had a formal point of contact with NEX-SAG and materials were exchanged.

There was cross-membership and interaction with other working groups convened by the Human Exploration Operations and Science Mission Directorates (HEOMD and SMD, respectively). These were:

- A joint HEO/SMD Human Landing Sites Selection (HLS^2) Steering Committee;
- The HEOMD ISRU (*In Situ* Resource Utilization) and Civil Engineering working group (ICE-WG);
- MEPAG Human Science Objectives SAG (HSO-SAG) requested by HEO/SMD.

HLS^2 integrated inputs from these groups to help define the nature of landing sites for human explorers on Mars and the varieties of resources anticipated to be needed for human exploration on Mars. An Integration Workshop involving all these groups and the NEX-SAG co-chairs was held on June 4-5, 2015.

Further input on resource objectives was sought and received via ICE-WG participation in subsequent discussions, including at the NEX-SAG face-to-face meeting in July. The ICE-WG recommendations are captured in a presentation (ISRU & Civil Engineering Needs for Future Human Mars Missions, henceforth ICE-WG, 2015). Considerations of the science that missions involving humans on Mars would conduct were also provided on the basis of the HSO-SAG final report (HSO-SAG, 2015).

An Interim Report was submitted to Prof. Lisa Pratt, MEPAG chair, on September 21, and forwarded to the Drs. Ben Bussey and Michael Meyer, the NASA Headquarters requestors of the NEX-SAG analysis. That report was a two-page summary of high-level findings and provided an opportunity for the conveners to apply any mid-course correction or to request any additional action. There was none. This full report was submitted for review by non-SAG members on October 27. This final report incorporated, as appropriate, responses to the comments and suggestions of the reviewers. For convenience and ready reference, Appendix 2 lists all Findings of this report, with their page numbers.

Tasks specifically requested of the NEX-SAG, again in abbreviated form as described in the Charter (Appendix 1), are described here.

Specific Tasks

I. Science. Identify and prioritize science objectives within each mission conceptual class. Objectives should address the NRC Planetary Science Decadal Survey (*Vision & Voyages for Planetary Science in the Decade 2013-2022*, henceforth "the Decadal Survey" and NRC, 2011) priorities and the likelihood that the identified measurement approaches exist today as flight-ready entities for a 2022/24 orbiter. New discoveries may also motivate specific objectives, but a strong rationale for these is required.

II. Exploration Resources. Identify remote sensing capabilities that can locate, characterize, and—where possible—quantify resources that may be needed to support and enable effective exploration by humans on the surface of Mars. Resource objectives were provided by the ICE-WG (ICE-WG, 2015).

III. Measurement Approaches. Identify measurement approaches needed to meet scientific objectives (I above) and to locate and characterize accessible resources (II). Identify synergies between these and/or the capabilities needed to conduct basic reconnaissance for landing site safety and access.

IV. Mission Scenarios. Identify mission scenarios with general mission timelines, orbit parameters, and payload combinations within the given range of mission concepts and capabilities considered.

V. Traceability. Show traceability to the Planetary Science Decadal Survey (NRC, 2011) and revised MEPAG Goals (MEPAG, 2015).

Mission Options

The Orbiter Study Team presented technical options for a 2022/2024 Orbiter and worked with NEX-SAG regarding potential mission capabilities. Key advances considered were the use of Solar Electric Propulsion (SEP) and advanced telecommunications systems (i.e., use of Ka-band and higher power RF amplifiers; possibly optical communications). Figure 1 encapsulates the range of options presented:

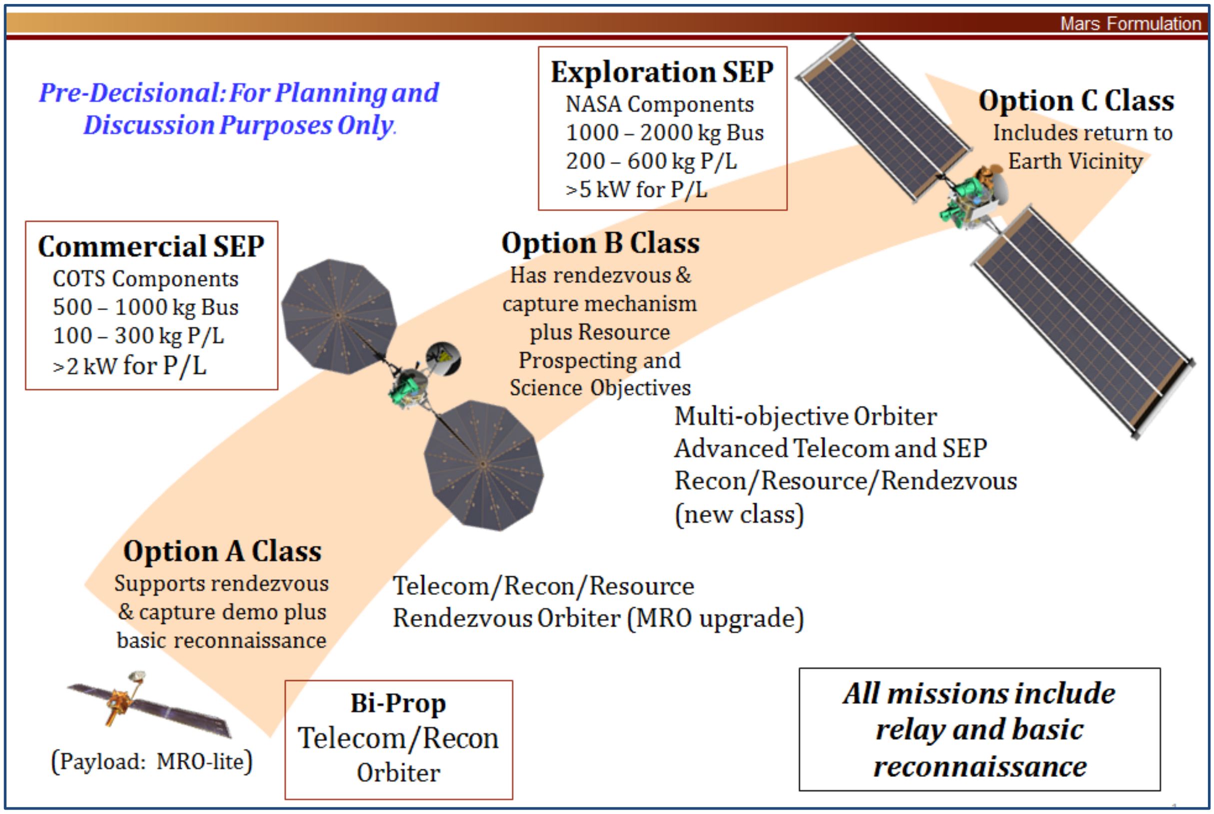
A. While a bipropellant (e.g., MAVEN-class) spacecraft may have payload capabilities of 100-200 kg and ~150 W (Figure 1), this class of spacecraft is envisioned as a highly cost-constrained mission supporting programmatic functions (e.g., relay and reconnaissance) plus the rendezvous and cache mechanism. That leaves up to ~80 kg for the remote sensing payload, including the high-resolution imager.

B. The use of commercially available SEP increases the payload capabilities to 100-300 kg and more than 2 kW available power with up to 200 kg for instruments. These capabilities are due to the lesser fuel load required by SEP and to the fact that much of the power generated by the large solar arrays required for a SEP-mission to get to Mars can be diverted to the payload once the spacecraft is in Mars orbit.

C. NASA has been studying the development of even more powerful SEP systems, with a view to their application for missions like ARRM. In this Exploration SEP option class the spacecraft could carry a payload of mass 200-600 kg, powered by more than 5 kW. At the higher end of capabilities in this class, the payload mass can be used to provide enough fuel to bring the SEP-powered spacecraft out of low Mars orbit and to return it to Earth vicinity. In that return option, the remote sensing payload would be restricted to ~150 kg and the Mars mission phase (including relay) would be terminated after ~5 years.

Option C was regarded by NEX-SAG as most interesting if it did one of two things: *1)* Actually returned a contained sample cache back to Earth vicinity, or *2)* accommodated the full payload needed to meet both resource prospecting and compelling science objectives. Clearly, possible options are still evolving, and depend on a number of factors and agency commitments that are still in flux. For options B and C, it may be difficult for NASA to fund payloads that could fully exploit the capabilities of advanced systems and that would include the many instruments and subsystems needed to address all desired functions. However, NEX-SAG notes that our international partners may be interested in participation and may help within these mission option spaces. There may be alternate payload options, including the use of daughtercraft, which could flourish in the more robust options. In any case, the advantages of using SEP, together with advanced telecommunications, quickly became apparent to the group.

Advanced Telecommunications: As will be shown below, advanced telecom (beyond MRO) is needed to return the increased data volumes produced by the high-resolution instruments envisioned by NEX-SAG while still achieving acceptable coverage. Such telecom would easily accommodate increased volumes of data returned by surface missions.



Mars Formulation

Pre-Decisional: For Planning and Discussion Purposes Only.

Exploration SEP
NASA Components
1000 – 2000 kg Bus
200 – 600 kg P/L
>5 kW for P/L

Option C Class
Includes return to Earth Vicinity

Commercial SEP
COTS Components
500 – 1000 kg Bus
100 – 300 kg P/L
>2 kW for P/L

Option B Class
Has rendezvous & capture mechanism plus Resource Prospecting and Science Objectives

Multi-objective Orbiter
Advanced Telecom and SEP
Recon/Resource/Rendezvous
(new class)

Option A Class
Supports rendezvous & capture demo plus basic reconnaissance

Telecom/Recon/Resource
Rendezvous Orbiter (MRO upgrade)

(Payload: MRO-lite)

Bi-Prop
Telecom/Recon
Orbiter

All missions include relay and basic reconnaissance

Figure 1. Artist-Conception of Potential Orbiters
This shows the increase in capability (mass/power) & potential use (options) for missions with Solar Electric Propulsion (SEP). Presented at the 30th MEPAG meeting (http://mepag.nasa.gov/meetings.cfm?expand=m30).

Solar Electric Propulsion (SEP): The use of SEP would open up new possibilities for improved, novel and collaborative measurement capabilities in pursuit of the mission objectives (Figure 1), which include:

- SEP can achieve the same velocity changes (delta-V) as chemical propulsion systems, while using a much smaller mass for fuel, although the thrusting is over a longer period than when using chemical propulsion. The reduced fuel load permits flight of significantly more payload mass. The large solar arrays required for SEP mean that once in Mars orbit, more power is available for payload use than previous missions have had. These enhanced payload mass and power capabilities can then be used to address the multiple functions and objectives of this orbiter.

- Increased payload mass supports trades between additional science investigations and technology demonstrations, possibly including daughtercraft carried into Mars orbit and likely communicating back to Earth through the mothership.
- Although it takes time, SEP can achieve orbit plane changes in a fuel efficient way. This enables successive observation campaigns through the ability to vary orbital parameters; e.g., gaining representative local time coverage from an inclined orbit and then polar coverage in a sun-synchronous orbit (see Figure 2 and Section IV).
- SEP provides a flexible, low-acceleration insertion into Mars orbit over an extended period and so eliminates orbit insertion as a "time-critical event". Additionally, using SEP, the orbiter could pause at the orbits of Deimos and then Phobos as it spirals in to low Mars orbit, enabling observations of the Martian moons during multiple fly-bys.
- As noted above, advanced SEP may enable the actual return of samples from Mars back to Earth vicinity.

Rendezvous and Capture of an Orbiting Sample Container/Cache (OSC)

The Decadal Survey stated that:

> "*The analysis of carefully selected and well-documented samples from a well-characterized site will provide the highest science return on investment for understanding Mars in the context of solar system evolution and for addressing the question of whether Mars has ever been an abode of life." (NRC 2011, p. 158) The Decadal Survey thus gave its highest priority for flagship missions to "the elements of the Mars Sample Return campaign*" (NRC 2011, p. 164).

When this study began, progress towards this goal was envisioned by the Orbiter Study Team to be a technical demonstration involving the release of, rendezvous with, and capture of an orbiting sample container (OSC) in low Mars orbit. NEX-SAG considered this capability to be part of the directives for a 2022/24 orbiter, meeting the program imperative to demonstrate progress toward sample return. As orbiter studies progressed, an option emerged for a SEP-powered craft that, in principle, could return a simulated or actual orbiter sample cache back to Earth vicinity (e.g., lunar orbit) at the end of a nominal 5-year mission in low Mars orbit. This return would end the Mars phase, including relay and reconnaissance, by this orbiter; at present, this seems justified scientifically only if the termination is to return an actual cache of Mars samples. (An option was studied that would split the spacecraft into two craft, leaving one to continue operations in Mars orbit. However, the needed duplication of telecom, command and data handling computers and other spacecraft subsystems appeared to be prohibitive.) A key point is that the decision to return could be made at the end of the 5-year mission in low Mars orbit (Figure 2).

The payload resources required for a technical demonstration of rendezvous and capture in Mars orbit were accounted for in the specifications (see Figure 1) that the Orbiter Study Team provided to NEX-SAG regarding what mass and power would be available for instrumentation needed to address objectives of Mars science, resource prospecting, and reconnaissance. Since the rendezvous and capture capability is still evolving, NEX-SAG notes that development issues could preclude other mission functions if limited to the Option A orbiter-class capabilities. SEP-class missions would be preferred even for the rendezvous and capture demonstration in Mars orbit, as SEP is clearly needed for the return of a sample container/cache. **The return of an actual sample cache to Earth vicinity would be a major achievement of NASA's Exploration Program**.

> **Finding 1*: NEX-SAG finds that a demonstration of rendezvous and capture or actual return of a retrieved container/cache to Earth vicinity would likely require SEP capability, especially if other high-priority resource and science objectives are to be pursued. Return of an actual cache of Mars samples would fulfill the Decadal Survey's highest flagship priority.***

The NEX-SAG was directed to study an orbiter possibly launched in the 2022-24 period (Appendix 1). (Note: The Orbiter Study Team adopted a more generic Next Mars Orbiter or NeMO descriptor.) NEX-SAG notes that a SEP-powered orbiter launched in 2022 would arrive in low Mars orbit in the second half of 2024, but could begin relay earlier (Figure 2). Its presence then would ensure availability of the surface monitoring and telecommunications capabilities needed to support the 2020 Mars rover at the beginning of its extended mission (assuming the 1.25 Mars year prime mission currently baselined for the 2020 Mars rover mission), backing up functions otherwise provided by continuation of earlier missions. In 2024, these missions – Mars Reconnaissance Orbiter, MAVEN and the Trace Gas Orbiter (launched in 2005, 2013, and 2016, respectively) – would all be well into extended missions. Should these orbiters still be working, overlap of their observations with this next orbiter would be extremely valuable for inter-comparison, calibration, and joint analysis (e.g., sounding and imaging radars), thereby leveraging past data into the future. Should any or all of those orbiters fail by 2024, this orbiter would fill a critical need for relay and site monitoring, supporting the 2020 Mars rover's extended mission, possibly adding time for sample collection and caching.

Once in place, the 2022 orbiter could also support the return to Earth of samples from Mars by providing the critical support functions of telecommunications and site-monitoring for the missions that would follow – including a flight mission that, assuming approval, could retrieve the samples cached on Mars by the 2020 Mars rover mission and then launch the cached samples into orbit for eventual return to Earth. In some orbiter study options, the rendezvous and capture capability would demonstrate a critical step in the ultimate return of samples; as noted above, in other options, this capability would actually be used to return the orbited cache back to Earth vicinity, for retrieval there. Both possibilities are suggested in Figure 2. For return of the real sample cache, Figure 2 assumes the lander with the Mars Ascent Vehicle (MAV) would be launched from Earth in mid-2026 (not shown) and the MAV would orbit the cache in early 2029, with a possible exit from Mars orbit initiated later that year. (The observational campaigns and intervening inclination change shown in Figure 2 are described in more detail in Section IV; the rationale for these is discussed -- here and in Sections I and II.)

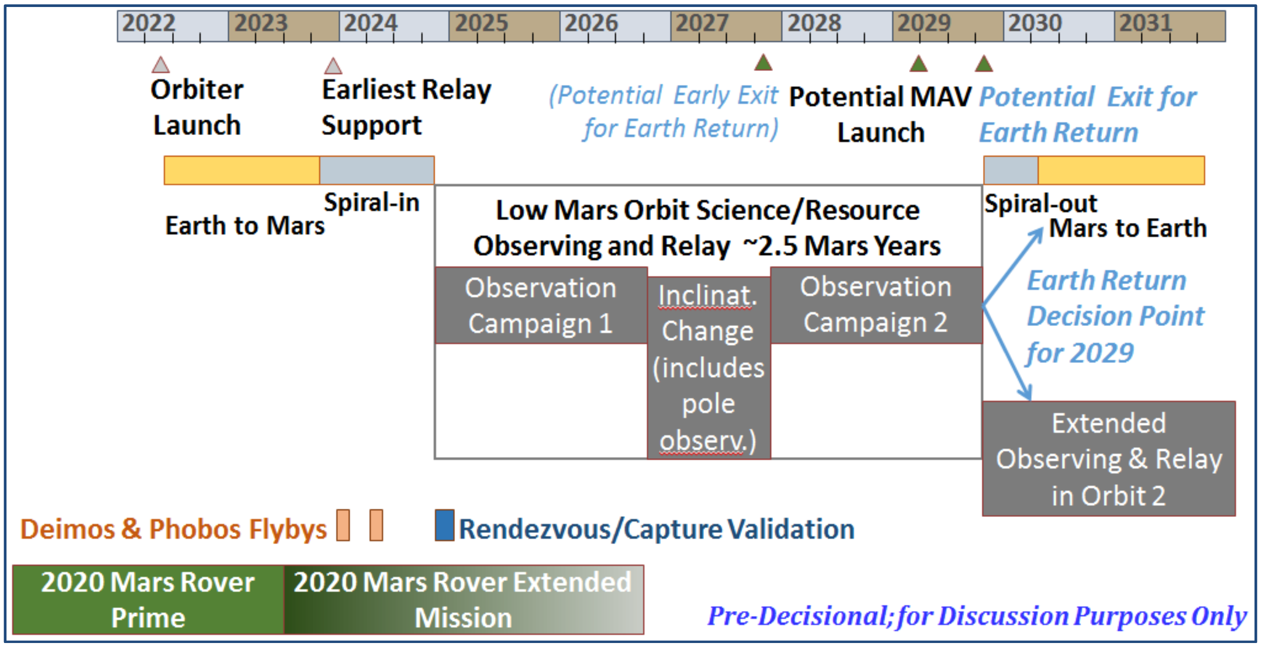


Figure 2. ***<u>A Notional 2022 Orbiter Mission Timeline</u>***

This shows potential support_to the planned 2020 Mars Rover (e.g., relay support) and to a possible future cache retrieval mission (with MAV) and possible return to Earth vicinity. Note the decision point for either Earth return or for continued observations and relay in Mars orbit. The Observation Campaigns are defined in detail in Section IV.

A 2022 orbiter would also accelerate, through its science and reconnaissance capabilities, identification and assessment of landing sites for future missions, particularly those supporting human explorers to be on Mars after 2030. This mission would provide critical data informing the architectural choices of future missions bringing humans to the surface of the planet, especially in terms of accessible *in situ* resources on Mars.

For all the reasons noted above, NEX-SAG finds an orbiter launched in 2022 to be most expedient to achieve the diverse objectives of the anticipated multi-function orbiter. ***Thus, in this report NEX-SAG will refer to the proposed orbiter as the 2022 Mars Orbiter, fully cognizant that other drivers may lead to a later launch.*** A later launch would stretch out the schedule for all activities, including progress on the resource prospecting and high-priority science observations, as well as the provision of critical telecommunications support for future missions and possibly contingency relay for the 2020 rover.

> **Finding 2*****: NEX-SAG finds that an orbiter launched in 2022 could be needed to provide critical support for the 2020 Mars rover and would help accelerate both potential sample return and preparations for human missions to Mars. A 2022 launch would also provide opportunities for inter-comparison and synergistic observations with existing orbiters, nearing their end-of-life.***

In the following sections, NEX-SAG addresses each of the charter tasks.

I. Science

NEX-SAG separated the charter task on science into: 1) making progress on sample return and 2) identifying compelling science objectives based on the non-sample-return guidance of the Decadal Survey and on objectives arising from new discoveries and analyses. The first is dealt with in the previous section. For the second, NEX-SAG has identified the following to be the highest priority science objectives for the next Mars orbiter (order does not indicate priority):

S-A. Understand the distribution and origin of water and CO_2 ice reservoirs: Polar science was recognized as a high-priority area for Mars and was discussed by the Decadal Survey as a possible candidate for the New Frontiers program, an openly competed class of PI-led missions of moderate to high complexity and cost (NRC 2011). Although not ultimately proposed as a New Frontiers candidate, subsurface ground ice science has taken on increased importance with detection of carbon dioxide ice reservoirs in the remnant polar ice caps (Phillips at el. 2011; Figure 3) and with recognition of the widespread nature of excess shallow water ice in the mid-latitudes revealed by radar (Bramson et al., 2015) and through exposure by meteorite impacts (Byrne et al., 2009)—phenomena that were still emerging from the extended mission studies of the Mars Reconnaissance Orbiter (MRO) at the time of the Decadal Survey assessment. Key scientific questions are how volatiles cycle between the poles and mid-latitudes, in the present climate, when and why these trapped reservoirs were created, and the quantity of volatiles sequestered.

S-B. Characterization and understanding of dynamic modern surface processes, especially the possible brine flows suggested by the observation of Recurring Slope Lineae (RSL). RSL are narrow (<5 m) albedo streaks that darken and extend downslope during the warmest seasons, then fade in colder weather, only to repeat in subsequent Mars years (McEwen et al., 2011; 2014; Ojha et al., 2013; 2014). RSL emerged after the Decadal Survey as a key focus area and are a prime example of recent paradigm-changing discoveries, with implications for the possibility of brines (salty, liquid water) on the surface today. Key questions include the geographic distribution of these features, the source(s) of moisture (ground ice, mineral deliquescence, or atmospheric recharge), their quantitative water inventory, and their habitability. The composition and inventory of salts may play a role in triggering RSL formation (Ojha et al., 2015), but certainly influence the water activity as a key geochemical parameter for habitability. In any case, these RSL are one of a class of modern surface phenomena that also includes active sediment transport processes (e.g., Bridges et al., 2012a; 2012b; Hansen et al., 2011; 2015); all these need to be characterized if we are to understand rates of surficial change and details of volatile sources and cycles, now and in the past.

The possibility of liquid water on Mars today raises the possibility of extant (present-day) life on the planet. Thus, RSL are potential targets for both biological and geophysical investigation. Ultimately, investigation by landed missions will be required; orbital remote sensing can further characterize these environments and determine which areas are most promising for future *in situ* exploration.

S-C. Characterization and understanding of current climate, water, and dust cycles, through observation of winds, water vapor, and temperature (even in the presence of dust) (Zurek et al., 1992). This would help us to better understand and to improve our ability to simulate atmospheric circulation and the transport of aerosols and volatiles, both of which feed into studies of interactions between the atmosphere and surface (e.g., RSL initiation, ice emplacement) and the triggers for dust storms, especially those that in some (but not all) years grow to planetary scale (MEPAG, 2015, Goal II).

S-D. Geologic evidence for major environmental transitions: The geologic records on Mars suggest significant environmental changes in the past, based on changes in composition. Observations from Mars orbit and on its surface over the last decade have revealed a complex array of ancient water environments, with observations of mineral composition and stratigraphic variation now complementing observations of surface geomorphology (Carter et al., 2013; Ehlmann & Edwards, 2014; Ehlmann et al., 2011; Murchie et al., 2009). Lacustrine, weathering, diagenetic, and hydrothermal aqueous environments with varying pHs and geochemistries have all been identified, with substantial new diversity [e.g., the prevalence of chlorides in paleobasins (Osterloo et al., 2010) and the widespread nature of hydrothermal minerals (Carter et al., 2013; Ehlmann et al., 2010; 2011)] discovered following the Decadal Survey deliberations. The specific variations in environments that occurred across the planet and at past times, and how that diversity evolved over time, is complex, and details remain unclear (Ehlmann et al., 2014). To make further progress requires improving the spatial resolution of mineral mapping to identify changes in stratigraphies and the continuation or improvement of very-high-resolution optical imaging.

S-E. Phobos/Deimos Fly-by Science: A SEP-powered orbiter must spiral in past the Mars moons on its way to low Mars orbit. During multiple fly-bys, the payload required to meet the prior science objectives (S-A through D) can provide significant new information that address outstanding questions about the Martian moons' interiors, composition, and surface processes (Murchie et al., 2015) and support possible future human exploration (MEPAG, 2015; P-SAG, 2012).

Science objectives achievable from Mars orbit (S-A through E above; also listed in Table I) are discussed in more detail in the following sections. **NEX-SAG is unanimous in its opinion that much high-priority science can be accomplished at Mars, particularly to follow up new discoveries that reveal the complexity of the planet and its evolution.** As noted above, many of these discoveries have only become widely known and their implications understood in the years since the NRC Planetary Science Decadal Survey deliberations.

The common thread linking science objectives S-A thru S-D is the increasing appreciation that "Mars is at the Edge" in terms of having more widespread liquid water activity on its surface than at present and that it may have been that way for a very long time (at least back into the Hesperian period, more than 3.5 Gyr ago) (Carr and Head, 2010; 2015; Ehlmann & Dundar, 2015). One possibility is that, for much of that time, water has transitioned between vapor and ice, with its sources and sinks moving around the planet as driven by obliquity-driven insolation changes at the poles (e.g. Carr and Head, 2010; Forget 2006; Head et al., 2003; 2006). In this view, liquid water at and near the surface was transient but recurring, as subsurface and surface conditions allowed liquid water to persist for a time, during portions of the Martian sol and season (Wordsworth et al., 2013; 2015). Thus, one hypothesis is that much of what we see on Mars today could be the result of relatively short-lived liquid water, recorded within landforms and mineralogies that we can observe (Ehlmann et al., 2011; Kite et al., 2013). The sublimation of known buried deposits of carbon dioxide ice may have prolonged the presence of liquid water in recent geologic times, by doubling or even tripling the present atmospheric pressure producing the most favorable periods (Phillips et al., 2011; Wordsworth et al., 2013). Overall, this provides a greater focus on the dynamic Mars of today and its more recent geologic past (late Hesperian thru Amazonian periods).

This perspective can be tested by mapping in greater detail the distributions of water and carbon dioxide on Mars today, particularly near the surface, and by advancing our understanding of their origin (Section S-A). Understanding the processes of volatile transport and sequestration also requires a detailed look at dynamic surface-change phenomena like Recurring Slope Lineae (RSL) and sediment transport (Section S-B). Since much of this transport is through the atmosphere, understanding how atmospheric state, circulation and transport change on modern time-scales ranging from diurnal, to day-to-day, to seasonal and interannual is needed, especially as new types of information are gained (e.g., winds; Section S-C). To build on our present ideas and time-evolution models for ancient and middle-period Mars requires a better understanding of the environmental transitions that occurred: Were they global or regional, did they occur repeatedly, were they contemporaneous, what are the geophysical/geochemical signatures (Section S-D)?

Looking beyond Mars, there is also the opportunity to advance our understanding of the Martian moons (Section S-E) given a SEP-powered spacecraft. All these science objectives are discussed in more detail below. They are followed by comparable objectives for the resource prospecting and strategic knowledge gap-filling activities supporting preparations for missions sending humans to Mars (Section II).

S-A. Distribution and Origin of Ice Reservoirs

A1. Distribution of buried water & CO_2 ice and relationship to surficial polar deposits

Subsurface water ice in non-polar regions

There is now abundant evidence for widespread, near-surface ground ice at mid- and high-latitudes from the Odyssey, MGS, MRO, and Phoenix missions (Boynton et al., 2002; Bramson et al., 2015; Byrne et al., 2009; Dundas et al., 2015; Feldman et al., 2002; Holt et al., 2008; Mellon et al., 2009; Mitrofanov et al., 2002; Plaut et al., 2009a; P. Smith et al., 2009). The distribution of this ice below depths of ~1 m, formation process, age of formation, "purity," and relationship to geomorphological units is currently unknown, although there are inferences. The presence of ice is suggested where neutron/gamma ray spectrometer measurements detect elevated hydrogen within the topmost meter of ground and is indicated directly by imaging and spectral analysis of craters exhuming ice deposits in these terrains and by radar imaging of subsurface layers with ice-like dielectric constants. However, many features of near-surface ground ice remain poorly understood, such as the thickness (and characteristics of overburden), the correlations with geology, and the relationship (if any) of ice deposits to lower-latitude features, including debris-covered glaciers (i.e., lobate debris aprons—see Holt et al., 2008; Plaut et al., 2009a) and possible tropical mountain glacier deposits (Head et al., 2005)).

Additional questions include: Is there enhanced chemical weathering associated with the ice? Do freezing-point depressants facilitate melting and chemical interaction with the regolith? Is shallow ice related to possible liquid-flow features (gullies, RSL)?

> **FINDING 3*: Measurements that could determine the location, thickness, concentration, and depth of buried ground ice – as well as the chemistry of associated mineral alteration and salts – are important for understanding the current climate and past climate cycles on Mars.***

Ice detection is most useful at spatial scales that can be related to geologic features such as partially shadowed regions within craters and landforms at similar scales. Unfortunately, the available neutron and gamma ray spectrometer footprints are ~300 km across. To make significant progress in this area NEX-SAG concludes that polarimetric imaging radar measurements with resolutions of ≤15 m horizontal ground scale and sensing depths of up to 10 m are needed to detect and resolve pockets of pure ice within the near-surface. A sounding mode (or separate radar sounder) could aid estimation of the depths to the ice table. Radar observations would benefit from complementary thermal measurements over diurnal and seasonal cycles, as this would place constraints on the depth of ice within the depths of the daily and annual thermal waves (a few to tens of cm). The thermal IR data may also reveal pore-space ice not detectable with radar.

Inventory of CO_2 in the poles

Within the south polar cap, MRO SHARAD discovered a large inventory of CO_2 ice (with its extremely low reflectivity) buried within the south polar ice cap, beneath a water ice layer and an uppermost thin layer of CO_2 ice (Phillips et al., 2011; Putzig et al., 2015; Figure 3). Due to the radar track-to-track spacing and the MRO orbit inclination, which does not include areas poleward of 87.4°S/N, the volume of CO_2 is not precisely known, but it is known to be at least large enough to more than double the present atmosphere, thereby expanding the possible periods and places where surface liquid water could have been stable in the geologically recent past.

> **FINDING 4*: Measuring the precise volume of the recently-discovered polar CO_2 ice reservoirs would better constrain atmospheric density during prior epochs, when obliquity cycle variations could have sublimated the current or similar buried CO_2 ice deposits and enabled liquid water to be stable for longer periods over more of the planet.***

SHARAD has broadly mapped the extent of these CO_2 deposits, but it cannot resolve or detect thin near-surface layers and possible small exposures of the otherwise buried deposits. Complete polar coverage with a radar capable of sounding to and resolving shallow depths (Section III) would enable more comprehensive mapping of the buried and surface CO_2 deposits and could be accomplished by a SEP orbiter, with its ability to adjust its orbit inclination in a fuel-efficient way. Estimations of surface frost amounts could also be provided through high-resolution imaging, and short-wave and thermal IR spectral mapping.

Subsurface and surface evolution of the caps and Polar Layered Deposits

Within both the North and South polar regions, MRO has expanded knowledge of layering in the polar caps and adjacent Polar Layered Deposits (PLD; Putzig et al., 2009; Holt et al., 2010, Phillips et al., 2011). These layers are likely caused by obliquity-driven climatic changes that promote dust deposition and/or variations in rate of ice deposition. The layering has very different character between the poles, revealing inherent changes in their evolution. Linking the radar-derived layering with the visual images of exposed layers (Figure 3) has been difficult because of the different wavelengths and spatial resolutions involved. Furthermore, the structure of the uppermost layers is not resolved by SHARAD nor by Mars Express MARSIS, the two sounding radars that have been flown to Mars.

A recent effort to map the shallowest unconformity resolvable by SHARAD within the polar layered deposits reveals an overlying quantity of water ice that is within a factor of two of that predicted by Head et al., (2003) to have been lost from the mid-latitudes during the retreat of the last Martian ice age beginning some 370 ka ago (I. Smith et al., in prep.)

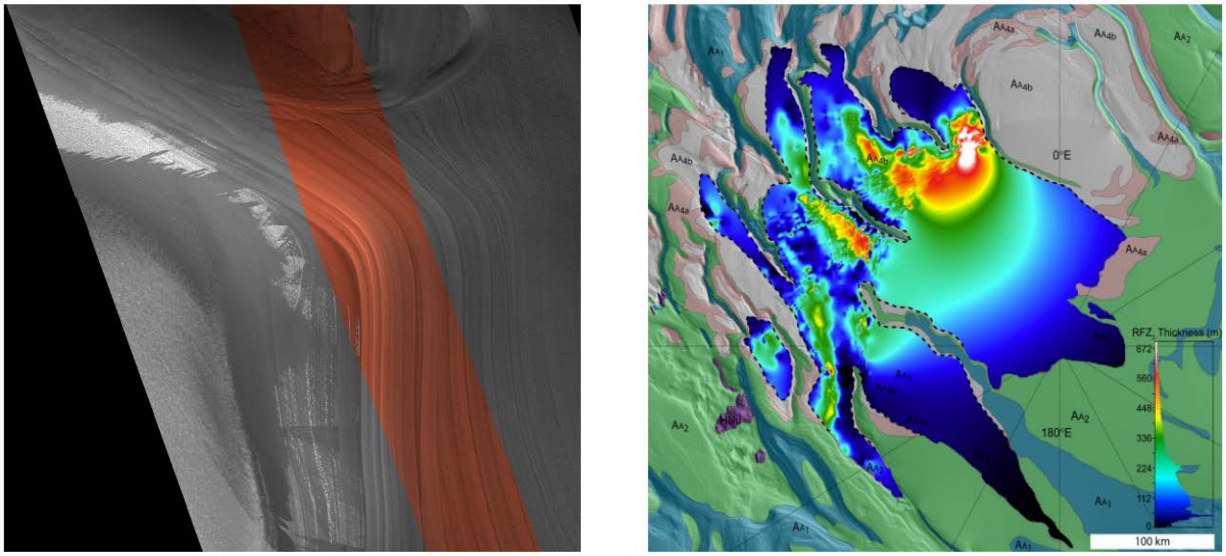


Figure 3. <u>Polar Phenomena</u>

(left) MRO HiRISE image with 1.2 km wide false color strip showing the top of the north polar ice cap and the many fine icy layers exposed at the cap edge (ESP-018469_2790_MRGB; U. Arizona/JPL/NASA). (right) Color shows the thickness of a radar echo-free zone beneath the south polar residual cap, believed to be a buried reservoir of CO_2 ice. The horizontal extent of the reservoir is correlated with a surface geologic unit (Phillips et al., 2011).

> **FINDING 5*: Knowing the timing of geologically recent climate variations is fundamentally important to understanding Mars. Measurements of the polar layers and the seasonal and annual evolution of near-surface layers needed to understand the evolution of the poles and the formation of lower latitude surface and subsurface ice deposits.***

An orbit enabling polar coverage is required (e.g., MRO type, or one that reaches higher latitudes). Improved vertical resolution sounding (e.g., tens of cm) of the uppermost hundred meters would provide data about how the polar layering changes on more recent timescales, including seasonal timescales. High-resolution color imaging is important for studies of fine-scale polar layer stratigraphy and stereo imaging is critical for correlation and characterization of polar layers across the cap. Short-wave and thermal IR observations are needed to track the seasonal changes in the distribution of water and CO_2 frosts and ices. Expanding the time baseline of polar data through a new mission would provide change detection baselines of decades and provide data for parts of the poles that cannot be studied using MRO.

A2. Volatile cycling between high and low latitudes

Recent missions have revealed aspects of the complex seasonal transfer of water and CO_2 between the poles and mid-latitudes. Seasonal (and longer-term) releases and deposition of water and CO_2 at high latitudes (e.g., the polar CO_2 venting and "swiss-cheese" terrain) have been observed in MRO HIRISE data (Byrne et al., 2008; Kieffer et al., 2006). Frosts (water and CO_2) have been observed to change seasonally (Thomas et al., 2013; Hansen et al., 2013), but their extent and relationship to features such as gullies, RSL, and the large buried CO_2 ice deposits are not yet understood.

Several types of measurements are needed to quantify seasonal transport of volatiles, including the properties and volumes (mass) of seasonal accumulations at the poles (thickness scales of meters for CO_2) and the further characterization of frost deposits (locations and times when present, discrimination between H_2O and CO_2).

> **FINDING 6*: Measurements over the diurnal cycle at sub-seasonal timescales are necessary to understand the recent climate history of Mars. Formation of snow and frost are highly sensitive to temperature change, as is volatile transport through the atmosphere. Characterizing the cumulative effect of these diurnally varying processes may be key to understanding the overall exchange between the poles and non-polar latitudes.***

Tracking movement of frosts should be undertaken at both global (one to tens-of-km using a wide-angle camera) and local (meter to tens-of-meters) spatial scales. Short-wave and thermal IR observations can track the appearance and disappearance of frost as a function of time of day and season, and differentiate between water and CO_2 frost. The presence and disappearance of frosts with seasonal and perhaps diurnal cycles are a key part of understanding volatile cycling. Radar sounding at higher resolution than is currently available could provide quantitative measurements of the thickness of polar seasonal deposits.

An approach to quantifying the seasonal sublimation and condensation of CO_2 is to measure the top of atmosphere energy balance, differencing measurements of reflected sunlight (integrated over visible and short-wave IR) and outgoing thermal IR radiation. CO_2 changes principally in response to this high-latitude energy balance. Most CO_2 condensation occurs in or near the polar night when the outgoing IR radiation is the dominant term. The effects of horizontal heat transport by the atmosphere can be estimated from temperature and wind measurements, with greater detail provided by models tightly constrained by those observations. A wide angle camera would also enable tracking of clouds throughout the days and seasons when the poles are in sunlight.

An orbit that can observe, at nadir, polar changes and polar clouds is obviously required. At least one Martian year in Mars orbit is required, with longer timescales needed to capture inter-annual variability.

S-B. Dynamic Surface Processes on Modern Mars

B1. Role of liquid water in Recurring Slope Lineae (RSL)

Recurring Slope Lineae (RSL, Figure 4) are a significant discovery since the Decadal Survey. During the warmer times of year, these long, linear albedo features darken and extend down steep slopes. During the colder seasons these dark lineae fade to the albedo of the surrounding terrain (McEwen et al., 2011; 2014; Ojha et al., 2014). To be classified as a RSL, the entire cycle must be observed in a subsequent Mars year. RSL morphology and spectral properties are most consistent with flow of fresh or briny liquid water or the action of deliquescent salts. RSL are relevant to many MEPAG goals and objectives. Assessment of their habitability requires information on chemistry and water activity.

> **FINDING 7*: Recurring Slope Lineae (RSL) are a significant discovery since the Decadal Survey. Their morphology and spectral properties are most consistent with flow on Mars today of liquid water, enabled by deliquescent salts or some other process. Understanding RSL processes and sources requires seasonal measurements of their morphology, chemistry, and temperature at high spatial resolution and as a function of time of day.***

MRO orbital constraints only allow RSL to be observed at 3 a.m./3 p.m. local mean solar time (LMST). Near-surface ground water is more likely to be liquid from mid-morning to early afternoon. Measurements over a diurnal cycle within ≤90 days (preferably ≤60 days) are required to understand water activity and to separate diurnal from seasonal change.

Because of their small spatial scales (frequently ~1 m in width), investigating RSL morphology requires imaging that resolves <1 m features (MRO HiRISE class or better), and color imaging at this scale is a particularly useful discriminator in identifying these features. Critically, many candidate RSL are at the HiRISE resolution limit. Therefore, with higher resolution (10-15 cm/pixel), currently identified features would be more fully characterized and smaller RSL could possibly be found, within both currently monitored and new locations. Stereo imaging would permit meter-scale elevation models for RSL, an important constraint on flow processes. Measurement of composition and temperature at the scale of large RSL or small RSL clusters (≤6 m across) is required to understand their hydration state and the presence of freezing point depressants, such as perchlorates or other salts (Dickson et al., 2013; Ojha et al., 2015). Spatial resolution of such measurements needs to be improved over current capabilities to fully characterize the RSL phenomenon. Siphoning of atmospheric water is suggested by the local geologic context. Currently, orbital remote sensing cannot directly observe water concentrations at the surface, but measurement of local-scale variations in water vapor in the lower atmosphere, seasonally and over the diurnal cycle, would constrain models of atmosphere-surface cycling (e.g., Grimm et al., 2014).

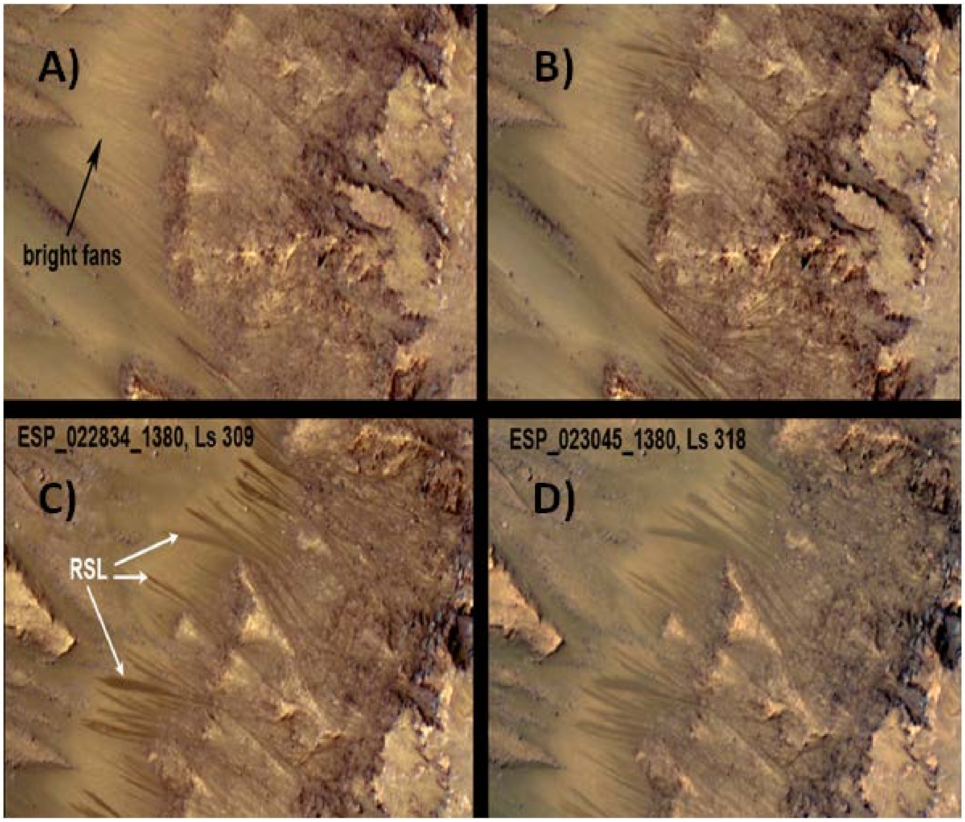


Figure 4. ***<u>RSL Example</u>***
Series of orthorectified images of Palikir Crater in Newton Basin showing: (A) faded RSL on bright fans from the previous Mars year and a hint of new RSL in bedrock regions; (B) new RSL appear; (C) the RSL lengthen downslope in early southern summer; and (D) the RSL are fading by mid-summer. MRO HiRISE / U. Arizona / JPL / NASA.

Strong dielectric contrasts linked with brines could also be a valuable indicator of liquid water, and could be detectable by polarimetric imaging radar at ~15 meters scale and at shallow depth (within a few meters of the surface). The ability of radar to probe below the surface could be key to tracing the source of subsurface water flow related to these features.

B2. Active sediment transport and surface change processes

The longevity and high resolution imaging from MRO have captured a variety of sediment movement on the surface of Mars. Continued high-resolution observations of sand dunes, ripples, gullies, landslides, dust devils, and wind streaks are needed to further characterize sediment transport and atmosphere-surface interactions. In particular, continued measurement of ripple and dune migration will show how aeolian sediment transport varies with season and interannual differences in Martian climate, will provide indications of near-surface wind direction for comparison to atmospheric models, and can identify activity in new areas of the planet (e.g., Bridges et al., 2012a; 2012b; Diniega et al., 2010; 2013; Dundas et al., 2012; 2015; Hansen et al., 2011; 2015; Russell et al., 2008; Verba et al., 2010).

> **FINDING 8:** ***Continued monitoring of dynamic processes in sand dunes, ripples, dust devils and localized regions of high dust loading will help in understanding aeolian volumetric sediment transport, near-surface convection, dust lifting, and dust storm initiation. Repeat imaging of dynamic surface changes, including gullies, will constrain the role of volatiles and sediment transport processes.***

These goals could be achieved over limited areas with a HiRISE-like (~30 cm/pixel) or better visible imaging capability. A higher-resolution optical imaging system (~10-15 cm/pixel) is likely required to detect and measure fine-scale surface changes on temporal scales of days or weeks, improving our understanding of the effects of surface winds on shorter timescales. High-resolution color imaging provides information on the nature of mobilized sediment, both in gullies and aeolian bedforms.

It is also important to combine observed surface changes with wind measurements in the lower atmosphere, as these could in principle yield new insight into threshold frictional velocities and the exchange with the surface. However, as described under Science Objective S-C, the vertical resolution and sensitivity to winds close to the surface appear to be beyond present orbital remote sensing capabilities.

S-C. Dynamic Processes in Current Martian Atmosphere

C1. Atmospheric circulation

The Martian climate system is controlled by the dust, water, and CO_2 cycles, which are fundamentally coupled to radiation and atmospheric circulations (wind systems). Measurements of winds, temperatures, water vapor and aerosols are required for a fundamental understanding of atmospheric circulation, transport, and the exchange of water and dust with the surface (M. Smith, 2008; Zurek et al., 1992).

Winds have essentially never been measured from orbit. Direct wind velocity measurements are required for the proper characterization of the structure and variability of the general circulation, particularly components that are not in balance with the thermal field (e.g., thermal tides). Simultaneous measurement of wind velocities and temperatures are required to fully understand the nature of the coupling between circulation patterns and the thermal structure (MEPAG, 2015, Goal II). Local time coverage is extremely valuable to eliminate aliasing of atmospheric variability. Together with wide-angle imaging, wind measurements and profiling of temperature even in dusty air could reveal new features of major events like local and planetary-scale dust storms. This should improve our understanding of the onset and evolution of these storms, which represent major components of seasonal and inter-annual variability.

Substantial understanding of atmospheric physical processes is gained through the use of general circulation models (e.g., Forget et al., 2013; Wordsworth et al., 2013). Observation of wind velocities, particularly when coupled with atmospheric temperature measurements, would greatly aid validation and improvement of these models. These observations would directly lead to improved confidence in our understanding of current atmospheric dynamic processes and would aid in the understanding of past climates.

Engineering designs for operations in the atmosphere have had to rely on numerical models of uncertain validity for winds and thus must include arbitrarily large margins on their environmental models to ensure successful performance. Lack of knowledge of wind velocity is a major source of uncertainty for Entry, Descent, and Landing (EDL) performance and accuracy for landing systems that use parachutes.

Horizontal wind vector velocities and temperatures at 0-80 km altitude, with vertical resolution of 5 km or better are needed to constrain components of the general circulation. Frequent, global coverage is needed to understand the circulation. This includes the polar regions, as the strongest winds and regions of storm generation are frequently near the polar cap edge. Local time coverage is extremely valuable to eliminate aliasing of atmospheric variability.

Wind measurements from nearer the surface (from a few to hundreds of meters) are of great interest, but present significant challenges for orbital remote sensing to achieve the vertical resolution needed for analysis. However, the wind measurements described above would provide important boundary conditions for models of both past and present wind patterns, and enable some comparison with geomorphology and observed surface processes (e.g., see Science Objective S-B2).

> **FINDING 9*: Observation of wind velocity is the single most valuable new measurement that can be made to advance knowledge of atmospheric dynamic processes. Near-simultaneous observations of atmospheric wind velocities, temperatures, aerosols, and water vapor with global coverage are required to properly understand the complex interactions that define the current climate.***

C2. Atmospheric transport and state

Dust and ice aerosol global distributions are intimately connected to each other and to the thermal structure and circulation patterns in the atmosphere (e.g., Heavens et al., 2011; Kleinbohl et al., 2015; Medvedev et al., 2011). A proper understanding of the dynamical and radiative processes that operate within the current Martian climate requires accurate aerosol, temperature, and wind profiles.

Processes controlling the global distribution of Mars atmospheric water are poorly constrained (e.g., Kahre et al., 2015). Few vertical profiles of water vapor currently exist, and lack key supporting temperature and cloud profile measurements needed to address poorly understood microphysical and transport behaviors associated with Mars atmospheric water and clouds.

The ability to retrieve atmospheric temperatures independent of dust loading would greatly improve our knowledge of atmospheric thermal structure, especially in the lowest two scale heights (~15 km) above the surface. And yet it is essential to obtain the aerosol profile as well in order to characterize both the radiative forcing of the atmosphere and its resulting circulation and state.

Minimal aerosol biasing of temperature and water vapor retrievals is needed to increase vertical coverage and accuracy. Multi-wavelength retrievals of aerosols, which enable determination of aerosol particle size, are also needed to characterize the radiative effects of atmospheric heating and cooling. Global coverage from 0-80 km with 5 km vertical resolution is desired for all observed quantities. This resolution is needed to determine global- and regional-scale transport of dust, volatiles, and trace gases, with implications for surface sources and sinks.

As noted earlier, high vertical resolution boundary layer winds and water vapor sampling are of high scientific value (MEPAG, 2015, Goal II). However, for boundary layer processes to be interpretable they must be sampled with very high horizontal, vertical, and temporal resolution. To quantitatively address surface-atmospheric exchange of Mars water, both temperature and water vapor must be measured within the lowermost few meters to several kilometers of the atmosphere, with accurate diurnal and vertical profiling capabilities. Similar vertical resolution would be needed for modeling ice stability within the polar regions and in locations with subsurface ice. Both objectives appear to be challenging for an orbiter alone, although orbiter observations would significantly complement future observations from landed meteorological packages (ideally a network).

> **FINDING 10*: Current orbiter remote sensing can provide boundary conditions for modeling exchange between the surface and atmosphere, but cannot achieve the vertical resolution needed for direct determination of fluxes of volatiles, mass and energy close to the surface.***

Previous orbiters have made observations that sample only a small range of local times, which has limited the analysis and understanding of important atmospheric physical processes such as atmospheric circulations and tides (planetary-scale oscillations driven by daily insolation), and the diurnal component of the water cycle and its interaction with the surface. Many meteorological fields and phenomena (e.g., location and optical depth of water-ice clouds) are likely to exhibit significant changes over the diurnal cycle (e.g., Lee et al., 2009). Observation of winds, atmospheric temperatures, aerosols, and water vapor over the diurnal cycle is needed.

Observations need to sample representative local times throughout the complete diurnal cycle over sub-seasonal timescales (< ~45° of Ls) to enable the separation of seasonal and diurnal variations.

> **FINDING 11*: Representative diurnal sampling on a timescale less than a Martian season is required to identify how atmospheric phenomena change with varying solar input and to remove aliasing associated with key measurements such as atmospheric temperatures and winds in the context of thermal tides.***

It is desirable to map atmospheric state quantities for multiple Mars years to understand interannual variability and decadal cycles and trends. Many variations and trends can only be detected using data that spans many Mars years. Multiple examples of unusual events such as global-scale dust storms are needed to get beyond the statistics of small numbers and to determine their underlying physical processes (e.g., Newman & Richardson, 2015; Zurek & Martin, 1993). Observations by a 2022 orbiter would build on earlier measurements, just as the timely arrival of MRO enabled extension of the MGS atmospheric, surface and polar records with little interruption, including the observation of the most recent planetary-scale dust event in 2007.

> **FINDING 12*: Continued observation of the general atmospheric state is required to evaluate further the degree of interannual variability and the presence of secular trends. A minimum set of daily global visual imaging, atmospheric temperature profiles, and daytime column amounts of dust, water ice, and water vapor is required to maintain the decades-long record begun by MGS, Odyssey, and MRO.***

The charter directed NEX-SAG to assume that missions in development but not yet launched, in particular the 2016 ExoMars Trace Gas Orbiter (TGO), would be successful. Given the emphasis of TGO on trace gas measurements, there was little incentive to include measurements of trace gases (other than water vapor and likely ozone) and isotopes in the 2022 Orbiter mission. The detection of trace gases like methane would have implications for the 2022 orbiter, with its objectives of detecting habitable environments (e.g., RSL?) and chemical alteration of surface and subsurface material by water (see Objectives S-B and S-D). While TGO cannot achieve a comprehensive survey of trace gases or isotopes, it is a highly capable mission and NEX-SAG felt that it was best to await its results before deciding on what the next steps should be in the area of trace gas detection and mapping. According to a presentation to NEX-SAG by the TGO project, TGO is slated to be in a diurnally changing orbit, but does not measure winds directly nor does it have atmospheric sounders that are insensitive to atmospheric dust. It does have a (collimated) neutron spectrometer. Upon arrival of the 2022 orbiter in 2023, inter-comparison of observations by TGO, MRO, and this next orbiter, even if observing at different local times, would be decidedly valuable.

C3. Daily global weather

Daily, near-global, visible light imaging creates weather maps that can provide key clues to atmospheric circulation and state by showing cloud and aerosol movement across the planet (e.g., Cantor et al., 2010; Wolff et al., 2014). The addition of ~2 appropriate SWIR channels enable these maps to also provide the context imaging of polar cap and seasonal frost changes. The addition of UV channels, such as on MRO MARCI (e.g., Clancy et al., 2014), also enables tracking of the column ozone, which is anti-correlated with water vapor by photochemical processes (Nair et al., 1994).

S-D. Geologic Evidence for Environmental Transitions

The last decade of exploration has revealed that interaction of ancient Martian materials with liquid water left mineralogical and chemical traces that are far more widespread and diverse that previously known (Carter et al., 2013; Ehlmann & Edwards, 2014; Ehlmann et al., 2011; Murchie et al., 2009; Osterloo et al.; Skok et al., 2010; Wray et al., 2011). Secondary mineralogies and associated morphologies are well-preserved in coherent strata from >3.5 Ga that vary in implied environmental setting from acidic to alkaline, hydrothermal to weathering, and lacustrine to diagenetic. Key outstanding questions, fundamental for understanding the interaction between early geological and climate processes, include:

(1) What is the nature of the Noachian crust and the relative prevalence of different types of parent materials that interacted with liquid water (extrusive volcanics, pyroclastic deposits, impact melt, or sedimentary deposits) and how were they affected by metamorphism (Carr & Head, 2010; McSween et al., 2015)?

(2) What were the primary sources of surface and ground water—rainfall or ice melt (Craddock & Howard, 2002; Wordsworth et al., 2013; 2015)?

(3) What is the relative prevalence of different environmental settings involving liquid water: surface water bodies, near-surface weathering, and diagenesis, hydrothermalism, serpentinization, and metamorphism at depth (Carter et al., 2013; Ehlmann & Edwards, 2014; Ehlmann et al., 2010; 2011)?

(4) What controls the observed spatial variability in geochemistry and mineralogy (Ehlmann & Dundar, 2015)?

Progress on these questions would lead to an improved understanding of the geologic evolution of Mars, reservoirs of volatiles and their exchanges, long-term evolution in habitability, and biosignature preservation. To make this progress, an improved understanding of the stratigraphy, mineralogy, age, and structure of Mars' ancient, well-preserved rock record is required. At present, our understanding is limited by both coverage and spatial resolution. Improvements in effective resolution continue to lead to new discoveries, including new minerals and new suites of alteration products with their associated structures. CRISM data reveal enormous diversity at 20-40 m/pixel but only a small fraction of the surface has been explored at high resolution—hence the record of ancient climate and geologic processes remains spotty.

> **FINDING 13*: Recent exploration has revealed enormous diversity in secondary mineralogies formed by reaction of liquid water with the ancient crust. Higher spatial resolution and broader wavelength range measurements of stratigraphy, mineralogy, and texture are required to understand environmental settings and biosignature preservation potentials of distinctive aqueous deposits >3.5 Ga in age.***

Mineralogy, morphology, stratigraphy, and texture are needed to understand the geologic record of ancient water and its implications for climate and habitability. SWIR wavelengths have proven effective at mapping secondary mineralogies (Ehlmann & Edwards, 2014). Improved SWIR spectral imaging systems with ≤6 m/pixel resolution would permit improved resolution of environmental/stratigraphic transitions and provide a closer link to the spatial scale investigated by current and future surface missions. These compositional investigations should be accompanied by imaging that can spatially resolve meter-scale structures or smaller (≤30 cm/pixel) to provide critical information on layering, bedforms, fractures, and alteration textures. Advanced visual imaging resolutions of 10-15 cm/pixel (2-3 times better than MRO HiRISE) would improve identification of bedding, to aid in determination of environmental setting. This advanced resolution would come at the expense of spatial coverage without an order of magnitude further increase in data return capability. Even higher resolution imaging (e.g., to resolve cobbles in flow deposits or to view diagnostic small-scale sedimentary textures, as the rovers can do) was judged to be beyond the capability of the orbiter pointing and stability capabilities being considered (Section III). Thus, the emphasis here is to go beyond the MRO capabilities by bringing the mineral and thermophysical mapping spatial resolutions closer to the existing (or modestly improved) MRO HiRISE and TGO CaSSIS resolutions, while expanding beyond the ~5% coverage that MRO will have achieved with HiRISE and CRISM, if they continue to operate until 2025.

Coupling thermal IR spectral observations over key wavelength ranges and comparable or smaller spatial scales to CRISM would improve characterization of secondary mineral assemblages and primary silicates. Beyond detection of alteration products, understanding the extent of alteration and quantifying reservoirs of volatiles on Mars requires estimates of quantitative abundances. Mixture models are beginning to provide quantitative estimates of minerals in these deposits, but large uncertainties remain. These uncertainties can be reduced by high-quality thermal IR spectral measurements to better constrain abundances of different minerals. However, NEX-SAG recognizes that definitive petrologic studies—combined mineralogy and rock texture—to determine environmental conditions of mineral formation require sub-mm scales not attainable from orbit and thus requiring *in situ* investigations.

A synthetic aperture radar in orbit would reveal the bedrock stratigraphy beneath mantling dust over vast areas of Mars. The SHARAD and MARSIS instruments are sounders, which provide cross-sectional views of the deep subsurface with rather coarse ground footprints and no polarimetric information. In contrast, synthetic aperture imaging radar like that carried by Magellan can achieve fine ground resolution (comparable to THEMIS-VIS), wide coverage, and probe the upper few meters of the surface materials. Ground-based Arecibo Observatory measurements (~3 km resolution and 12.6-cm wavelength) penetrate the upper 1-2 m of the dust to highlight buried fluvial channels and volcanic flows, but an orbital system operating at a longer wavelength (e.g., ~60 cm) could attain a five-fold greater penetration depth and at least 100-fold finer spatial resolution. This penetration capability, along with the polarimetric measurements, is clearly a requirement for the detection and mapping of shallow ground ice, but it also makes the radar an asset for understanding the often obscure bedrock geologic setting related to localized detections of hydrated minerals and potentially habitable environments.

S-E. Phobos/Deimos Science during Multiple Fly-bys

With SEP, the 2022 orbiter would spiral past the orbits of Phobos and Deimos (although most likely not within the moons' orbital planes). During possible fly-by encounters with the moons, instruments capable of investigating RSL and shallow water ice (e.g., high-resolution imaging, thermal and short-wave infrared mineral mappers, polarimetric imaging radar) could make significant contributions to the study of Phobos and Deimos, addressing both MEPAG and HEOMD goals (Murchie et al., 2014; Pieters et al., 2014; P-SAG, 2012). In contrast, a 2022 orbiter using a chemical propulsion system would likely have to choose between the Martian moons or Mars itself as its objective.

The most basic question about the moons is their relation to each other (Murchie et al., 2015). In particular, the densities of the two bodies cannot currently be compared as an indicator of a shared origin, because of uncertainty in Deimos' shape (and thus, volume). Similarly, comparison of surface crater-ages and appearance, and what this would imply about the near-surface structure and surface evolution at each moon, is impaired by a lack of imaging coverage and resolution for Deimos comparable to that now available for Phobos. An improved global volume estimate of Deimos, especially if accompanied by improved imaging resolution over most of Deimos, would enable comparison of the moons and a check on whether or not they are likely to share an origin. In addition, short-wave and thermal IR spectral measurements of the moons' surface, with higher spatial resolution and more complete coverage, would provide needed surface mineralogical composition information, which could also yield important clues about the moons' origin(s). Thermal IR imaging could also be used to determine layering, surface roughness, and rock abundance, as well as help place Phobos and Deimos within the context of TIR telescopic studies of airless bodies. Similar to radar studies of the Earth's moons, imaging radar observations of the Martian moons would be sensitive to subtle changes in the composition of the regolith within the upper-meters and could see beneath the space-weathered exterior. Such investigations are of interest to both science and exploration (SKG) objectives (see Table VI for traceability).

> **Finding 14*****: The use of SEP and the payload capabilities needed to address the reconnaissance, resource, and science objectives at Mars allow high-value science observations of Phobos and Deimos necessary to plan future missions to these moons.***

However, we recognize that not all science objectives at the moons can be achieved by this orbiter nor can all Strategic Knowledge Gaps (SKGs) at the moons be addressed (e.g., interior and high-fidelity surface composition, near-field gravity). To address some objectives would require a prolonged proximity operation near or on the moons' surface (versus fly-bys) and measurements taken within a range of illumination and observing conditions, which would likely not be within a Mars orbiter's delta-v budget. NEX-SAG did consider the possibility of dropping a hard probe onto one of the moons for observation of the resultant ejecta and the crater. However, the delivery and contact velocities needed to penetrate sufficiently into the expected thick regolith appeared to be prohibitively high. In summary, this orbiter would generate high-value SKG and new science observations of the Martian moons during fly-by encounters. To gain further information about the moons (e.g., near-surface gravity and internal composition) would likely require a mission focused solely on the moons (e.g., orbiting and/or landing on them), at the expense of the Mars-focused resource and science objectives discussed here.

II. Resources, Strategic Knowledge Gaps, Reconnaissance

NEX-SAG was directed to identify synergies between Science Objectives and potential Orbiter aims regarding identifying of resources, addressing human exploration Strategic Knowledge Gaps (SKGs), and Reconnaissance for landing site certification and characterization. The considered resource and SKG Objectives are outlined in Table II (RS-A through E).

Resources & Strategic Knowledge Gaps

Much is known about the environments of Mars thanks largely to past missions, and especially to the systematic global surveys, targeted observations, and landed analyses that have occurred in the last 20 years. However, there are many Strategic Knowledge Gaps (SKGs) that remain in our understanding and our environmental models. Filling these gaps has taken on greater urgency as NASA considers how to deploy humans to the Martian surface, enable them to explore while they are there, and to return safely to Earth—possibly as early as the 2030's. Extended stays on the planet may only be possible if the integrated Mars program can find *in situ* resources that can be exploited to sustain and protect human explorers in Mars vicinity and aid their return to Earth.

The highest priority resource objective is to find water, as it can be used in such diverse applications as life support, surface construction, and propellants for surface operations and ascent from Mars. To be useful, the water resource needs to be accessible from the surface, most likely in the form of ice or hydrated minerals. However, data on geotechnical characteristics (slopes, surface textures, load bearing strength and other mechanical properties) and mineral resources – e.g., construction materials, in addition to mineral-based ISRU – would also be valuable to planners of human expeditions operating on the surface of Mars. Thus, key resource objectives are:

RS-A. Find and quantify the extent of shallow ground ice within a few meters of the surface and characterize its ice-free overburden;
  - <10 m, shallower is better; desire <2 m of overburden;

RS-B. Identify deposits of hydrated minerals as a water resource, and potential contaminants within those deposits; map the distributions of possible special regions (e.g., RSL);

RS-C. Identify site-specific mineral resources and well-quantified geotechnical characteristics.

RS-D. Extend the atmospheric climatology with diurnal coverage and wind measurements;

RS-E. Provide key information for the exploration of the Martian moons.

Presently, the higher priority for human exploration (ICE-WG, 2015) is to find water (Resource Objectives RS-A & RS-B) and to gather information about the Martian moons (RS-E). This may change as planning for future human operations on the surface of Mars continues to develop and strategies for the engineering of the sites in support of humans evolve.

The approach to finding these resources are compatible with that found to be practical for science: Global and regional reconnaissance, followed by targeted very-high resolution imaging observations of promising sites, and finally verified and augmented by follow-on missions to the surface.

RS-A. Water Resources: Ground Ice

The first major resource of interest is ground ice, in the form of relatively pure slabs or lenses near the surface or within an ice-saturated regolith. The challenge is to detect ice that is shallow enough for utilization, but likely not exposed at the surface, assuming that some mantling is required to preserve the deposit from sublimation. This results in two investigations: detection of very shallow water ice (RS-A1) and characterization of the dry overburden in terms of thickness, composition, hardness/compactness and other physical properties (RS-A2).

While it is known by remote sensing (Mars Odyssey) and ground validation (Phoenix) that there is much ice in the upper meter of regolith at the higher latitudes (Figure 5), the ground ice that would be accessed by human explorers needs to be within ±50˚ of the equator due to dynamic constraints on launchers and to solar energy needs. We know from the MRO and Mars Express sounding radars (SHARAD and MARSIS, respectively) that there are disjoint locations of subsurface ice in the 40-50˚ latitude zones at depths >10 m (e.g., Plaut et al., 2009b, Bramson et al., 2015), but an overburden of dry material that thick is undesirable from the standpoint of resource exploitation (ICE-WG, 2015). Meteor impacts into the surface have occasionally revealed very bright deposits of ice – some at shallower depth (<5 m) in this latitudinal transition zone in the shallow subsurface (Byrne et al., 2009); their albedo and the rate at which the bright patches disappear suggest pure ice. The question here too is: How deep is the top of the ice layer and, between one and a few meters depth, how extensive might the near-surface ice be?

In discussions with the HEOMD ICE-WG, a depth of dry overburden no greater than 1-2 m was deemed reasonable for excavation planning, assuming other characteristics are amenable to excavation. Such deposits may exist due to localized micro-climatic conditions, so any effort to find and map them for ISRU-focused investigations would require spatial resolutions much finer (e.g., ~15 m) than those achieved to date by orbital neutron/gamma-ray sensing (100's of km).

Polarimetric imaging radars (PSAR) could detect relatively pure deposits of ice at depths of a few meters (<10 m, shallower depending on crustal composition). Polarimetry, at least dual circular measurements, is needed to detect the coherent backscatter signature from ice (e.g. Harmon et al., 1994). Thermal measurements obtained over a diurnal or seasonal cycle should also detect the presence of very shallow (<1 m) pure or pore ice. Combining both techniques can locate both pure and pore-space ice at various shallow depths.

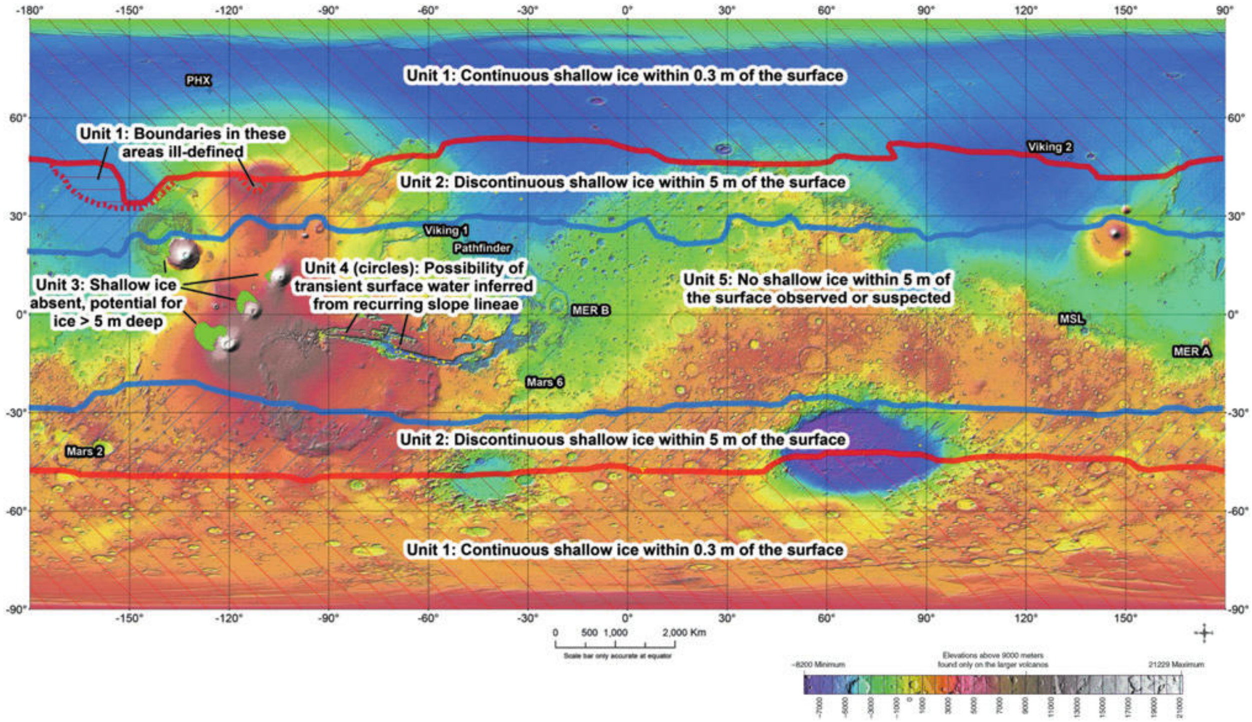


Figure 5. <u>Characteristic Regions of Subsurface Ice and Possible Transient Water</u>
The map is based on orbiter data and model inference of the depth and spatial continuity of shallow ground ice or potential transient surface water. Map background is MOLA digital elevation model of Mars in simple cylindrical projection. Figure is from Rummel et al. (2014).

The properties of the overburden (depth to the ice layer, thermophysical properties) can be assessed using a combination of radar sounding and thermal IR data. A thermal IR mapper would provide diurnal and seasonal ground temperature variations that can be used to model the upper tens of cm to a meter, including estimates of density and rock abundance (Bandfield et al., 2011; Nowicki & Christensen, 2007; Mellon et al., 2008; Putzig & Mellon, 2007; Putzig et al., 2005). PSAR in a sounding mode could provide an assessment of subsurface rock abundance in the upper several meters of ground, especially when combined with IR and visible optical data. In some cases mantling layers can be estimated through changes in backscatter (e.g., Campbell et al., 2015; Watters et al., 2007), but SAR imaging alone cannot directly yield the depths to the ice table. Operating at significantly higher frequencies than the 15- 25 MHz of SHARAD, a 2022 orbiter radar sounder or sounding mode of a SAR could yield the depth to interfaces between ice-rich layers and an upper mantling layer (e.g., Bramson et al., 2015; Putzig et al., 2014) and do so at depths (>1 m) greater than can be derived from thermal IR data alone. Modeling of the sounder data could provide an estimate of the dielectric constant, and thus density, of the overburden outside of areas with high surface clutter. Given the difficulties with interpretation for each instrumental approach, definitive identification of an interface as an "ice table" and characterization of its overburden would likely require data combination of data sets.

Continuing to look for new impact craters is difficult without the coverage achievable with intermediate resolution camera similar to the MRO Context Camera. In addition to the random arrival of the impacts, there is a strong observational bias in that new craters are most readily identified in regions with thick dust covers, as the impactors produce dark splotches in high-albedo (dusty) terrains.

> **Finding 15:** ***A combination of thermal IR mapping and polarimetric imaging radar, especially if augmented with a sounding mode, should be able to detect ice within a few meters of the surface and to estimate the depth and physical character of dry material above it (overburden).***

RS-B. Water Resources (and Contaminants) within Hydrated Materials

The second major resource of interest is hydrated mineral deposits, which have been inferred in a number of locations on Mars based on their infrared reflectance properties (Figure 6) (Carter et al., 2013; Ehlmann and Edwards, 2014; Ehlmann et al., 2011; Murchie et al., 2009). From the ICE-WG, a water content of approximately 5% is considered the minimum for practical *in situ* extraction from such deposits. Gaps remain, however, between current methods for quantitatively determining hydrated mineral abundances from orbital data and the development of constraints on the volume of resources within a chosen region for exploration by humans. Spectroscopic techniques alone yield uncertain estimation of the accessible water content as there is ambiguity about whether the observed mineralogy represents bulk rock, coatings, or adsorbed water, and there are currently limitations to radiative transfer theory for coherent, non-porous materials (Audouard et al., 2014; Milliken and Mustard 2007a; 2007b). Additional information, such as thermal IR spectral imaging at comparable resolution to short-wave IR spectroscopy and over multiple times of day, is needed to inform the modeling of mineral suites and the extent of particular deposits. Spatially correlating such measurements with high-resolution images would enable identification of useful deposits/landforms. Eventually a landed mission would be required to evaluate the potential of deposits detected at the surface, but orbital coverage is first needed to identify and characterize the lander sites.

> **Finding 16:** ***High-spatial-resolution observations in the short-wave IR with sufficient spectral resolution, aided by thermal IR spectral mapping, can identify hydrous minerals exposed at the surface, although with uncertainties in extrapolation to water content at depth. Extrapolating hydration at the optical surface to the subsurface accurately depends on the types of minerals present, dust cover, and the presence of adsorbed water especially at low latitude.***

From a resource exploitation perspective, not all hydrated minerals are of equal value. The efficiency of water extraction may be as important as the water content. In addition to the detection of hydration, it is also necessary to detect contaminants that can disrupt processing/extraction techniques. Existing mineralogical information show that some of the rocks and soils present on Mars contain species (e.g., perchlorates, sulfates, chlorides) that could be contaminants to catalysts used in chemical processing. Regolith material measured in Gale Crater by MSL has up to 3% water by weight (Leshin et al., 2013); such materials may actually be preferred, for example, to assemblages rich in sulfates that have higher water content, but also have the potential to disrupt chemical processing.

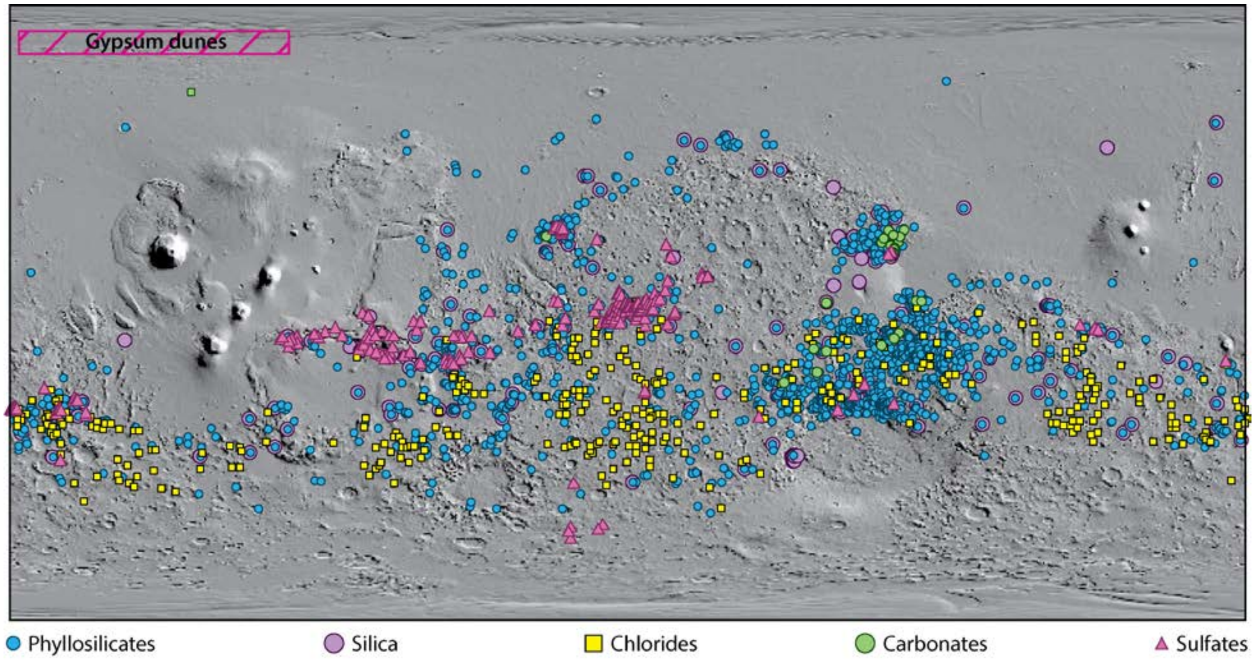


Figure 6. <u>Observed Outcrops of Minerals That Formed in Liquid Water</u>.
Depending on their hydration state and volume, these deposits may provide resources for human missions to exploit on Mars. Figure is from Ehlmann & Edwards (2014).

This is an area where a much better understanding is needed of which hydrated components (e.g., sulfates versus clays), in what quantity and context, could be used as a resource in practice. From orbit, remote sensing in the near to mid to thermal IR could identify minerals exposed at the surface and improved spatial resolution mineral mapping with imaging could address the issues of lateral uniformity. However, ground truth would be needed to confirm detections and quantities of the minerals. More importantly, the depth extent of any given mineral or hydrated phase can – from orbital data – only be inferred indirectly.

> ***Finding 17: A better understanding of which hydrated minerals can provide a practical resource to support humans on Mars is required, so that prospecting from orbit can be focused appropriately.***

RS-C. Mineral Resources and Geotechnical Characteristics

This third resource objective considers what may be called "<u>construction materials</u>". Both the requirements and the ability to identify the needed materials are still evolving and may be difficult to quantify from orbit. If the "construction materials" are complex in nature, such as those to be used to grow food and/or manufacture fiber, then even more work is needed before we can define the requirements for identification from orbit. NEX-SAG did not penetrate these areas to any significant degree, except to note that mineral detection and thermophysical properties of surface materials could opportunistically provide some clues as to the utility of the materials present.

Planning and building habitats for human explorers on Mars requires knowledge of the local terrain, compositional and thermophysical properties of surface materials, and near-surface structure. Promising sites can be identified with high-resolution imaging (≤30 cm/pixel), short-wave IR spectroscopy, thermal IR multiband imaging at different times of day, and polarimetric imaging radar.

RS-D. Characterization of the Martian atmosphere

Needed atmospheric observations are designed primarily to enable refinement and validation of atmospheric numerical models. As such, they need to be global and to sample a large range of times and environmental conditions, to make it more likely that the numerical models will capture those events most likely to be hazardous to spacecraft flying through the Mars atmosphere. In particular, the aim would be to globally monitor dust, temperature, and wind at all local times, including under very dusty conditions. Such investigations would require planet-spanning images for visual daily weather monitoring, as well as wind, temperature, and aerosol profile observations from the near-surface to 80 km, with a vertical resolution of ≤5 km. These measurements would include observations taken over a range of dusty conditions, including (if available) a global dust storm.

RS-E. Identify geologic units and constrain densities of Phobos and Deimos

Fly-by encounters with Phobos and/or Deimos could make significant contributions to our understanding of the structure and surface properties of Phobos and Deimos, and address both MEPAG (Goal IV) and HEOMD (SKG) goals. In particular, characterization of regolith properties such as surface roughness/slope and surface mechanical properties would aid studies of potential landing sites; characterization of their composition and near-surface structure would advance the identification of resources for potential human missions; and study of the gravitational field, libration rates, and interior density variations and would aid landing and rendezvous studies. Such investigations would utilize full-body imaging from a range of phase angles (to generate Deimos' shape model), high-resolution imaging and short-wave/thermal IR spectral measurements of the surface morphology, composition, physical characteristics, and radar observations of the near-surface structure.

Synergies between Science & Resources/Strategic Knowledge Gap (SKG) Objectives

Because the occurrence of water on and near the Martian surface is relevant to numerous climatic and geologic questions, one area of strong synergy between science and resource priorities for the 2022 Orbiter is associated with determining the extent of ground ice and the characteristics of its overburden within 50° of the equator and the possible location of ice reservoirs (if any) associated with RSL (S-A, S-B, RS-A).

A second area of high synergy between resource prospecting and science hypothesis testing centers on hydrated minerals. Science measurement requirements for characterizing the mineral record of past climatic transitions and salts potentially associated with RSL match requirements to identify and map the surface exposures of hydrated mineral deposits and "construction materials" as potential exploitable resources (S-B, S-D, RS-B, RS-C).

A third area of strong synergy is between requirements to better define the environments that future missions would operate in (filling SKGs) and measurement to understand the structure and dynamics of the lower atmosphere (S-C, RS-D). The atmospheric SKGs are addressed by capturing atmospheric variation, including the daily variation of density, since the diurnal variation over much of the planet is the second largest category of variation after seasonal effects – larger than day-to-day variations, outside the polar margins. The needed measurements are of wind velocities, temperature, and dust. This would reduce reliance solely on models at the times and places where data are acquired. Comparison of data with models would also help improve the atmospheric models for times and places without data. Regarding the surface, studies determining the physical nature of surface materials would address both geotechnical and resource questions, as well as investigations of the processes that lead to the formation of the rocks (S-A, S-B, S-D, RS-A, RS-B, RS-C). The needed measurements are high-resolution visible, SWIR, and thermal IR imaging of the surface, as well as radar to look at the near-subsurface. The degree of need depends on the future designs of landing and surface operating systems.

A fourth area of strong synergy is in the investigations of the Martian moons, Phobos and Deimos. Very similar measurements are needed to address both the primary science objectives and many of the small-body and Mars vicinity related SKGs (S-E, RS-E).

> **Finding 18:** ***NEX-SAG finds that there is strong synergy between the various required functions as a single instrument may address one or more of the science objectives and one or more of the resource, and reconnaissance needs. Four particularly strong areas of synergy include: i) the location of ground ice, ii) the characterization of hydrated minerals, iii) the structure and dynamics of the lower atmosphere, and iv) the moons of Mars.***

Reconnaissance and Telecom

NEX-SAG was directed to assume that telecommunications, critical event coverage, and reconnaissance for certification of landing site safety would be mandated for any orbiter mission. With regard to telecommunications, typically the amount of data relayed from the surface is a small fraction of the total returned by the orbiters. This may change as more sophisticated systems are landed on Mars and even more so when humans arrive. However, many objectives outlined by NEX-SAG require instruments with improved, very high spatial resolution; this increases returned data volumes by about a factor of up to 10 over existing capabilities, if comparable coverage is to be achieved. While onboard data compression and high-level processing may help in this regard, an increase by a factor of at least 3 in data return seems necessary and within reach for a 2022 Orbiter. The measurement approaches in the next section assume this increase in downlink would be achieved for the 2022 Orbiter, as postulated earlier.

> **Finding 19:** ***Improved telecom is required to acquire the higher-spatial resolution data sets needed to make significant progress on key resource and science objectives. A full order of magnitude increase, through systems such as optical***

> ***communications, would be required to achieve spatial coverage, at these higher-spatial resolutions, beyond a few percent of the planet.***

Reconnaissance has traditionally (e.g., MRO) been divided into identification, characterization, and certification. The last function is assumed to require resolution at least comparable to that of the MRO HiRISE imaging system (~30 cm/pixel) for rock distribution studies and meter-baseline slope determination from stereo image pairs. An improvement by a factor of 2-3 in this resolution would eliminate the need to extrapolate to estimate hazards, as rock size frequency distributions, meter-scale slopes and low cohesion aeolian deposits could be directly determined in 10-15 cm/pixel image data. From the instrument point of view, such an increase in resolving power may be possible within the HiRISE resource envelope of mass and power, given new technologies in electronics and light-weighting of mirrors. However, there is a corresponding development required in the ability of the spacecraft to accurately point and maintain stability during image acquisition. Additional work is needed to demonstrate that this can be achieved.

> **Finding 20:** ***HiRISE-class imaging (~30 cm/pixel) is required for landing site certification for future missions. An improvement to ~10-15-cm resolution would enable significant advances in science, and may be technically feasible so should be considered as resources permit.***

Even higher spatial resolution (~5 cm/pixel) imaging could assist rover traverse planning and would aid identification of smaller-scale hazards on the surface. NEX-SAG concluded that such an instrument would be difficult to achieve for development of a 2022 orbiter, as discussed in Section III.

> **Finding 21:** ***Although enhancing for many science objectives and helpful for rover operations planning, NEX-SAG concluded that ultra-high-resolution optical imaging (~5 cm/pixel or better) poses major accommodation challenges.***

The identification and characterization of possible landing sites for future missions currently utilizes mineral and thermophysical property mapping, atmospheric sounding, global imaging, and high-resolution targeted visible and SWIR images. Atmospheric sounding, in addition to providing environmental data for design, would provide a near-real time atmospheric monitoring function. Daily global images would provide warning of dust storms that could adversely affect solar-powered surface assets.

These capabilities are employed today as part of reconnaissance and NEX-SAG assumes that they will continue to be desired. The addition of polarimetric imaging radar would yield information about the near-subsurface structure, especially in the detection of water ice lenses.

Thus, there is considerable synergy between the science objectives (Section I) and the HEOMD SKGs.

Finding 22: ***Identification and characterization of future landing sites should include atmospheric monitoring to improve environmental models, ground ice prospecting, and mineral mapping to characterize potential landing sites in terms of resource access and of scientific regions of interest. Orbital monitoring of dust storms and of surface asset location would aid planning for missions while operating on the surface.***

Table I: Traceability of Measurement Objectives for Science

Program Aspect	Relation. to NASA Goals	Science or Exploration Objective	Investigation	Required Measurements	
MSR	Primary Decadal Survey Priority	Progress on Sample Return	Rendezvous & Capture in Mars orbit		
Science	High Decadal Survey Priority	**S-A.** Distribution & Origin of Ice Reservoirs	**A1.** Distribution of buried water & CO_2 ice plus relationship to surficial polar deposits	Extent & volume of water ice in non-polar regions	
				Extent & volume of buried CO_2 ice in the polar caps	
				Shallow subsurface structure of polar cap & layered terrain	
				Improved mapping of cap morphology, structure, & composition - as a function of season	
			A2. Volatile cycling between high & low latitudes	Seasonal mapping of surface water & CO_2 frost	
				Polar radiative balance: visible & thermal IR wavelengths	
				Polar atmospheric environment: Water vapor, temperature, wind, clouds	
	New Discoveries /High MEPAG priority	**S-B.** Dynamic Surface Processes on Modern Mars	**B1.** Role of liquid water in Recurring Slope Lineae (RSL)	Fine scale morphology	as a function of season & time of day
				Mineralogy, hydration state, & surface temp.	
				Water vapor changes within lowermost atmos.	
			B2. Active sediment transport & surface change processes	Sediment flux in key locales: including dunes, gullies, dust streaks	
		S-C. Dynamic Processes in Current Martian Atmosphere	**C1.** Atmospheric circulation	Vertical profiles of horizontal wind components & T(p) with good precision, even in dusty atmosphere changes	
			C2. Atm. transport & state	Vertical profiles of aerosol (dust & ice) & water vapor	
			C3. Daily global weather	Daily global mapping of dust, clouds, & surface frost	
		S-D. Geologic Evidence for Environmental Transitions	Diversity of ancient aqueous deposits	Fine-scale composition & morphology in ancient terrain	
	Martian moons	**S-E.** Phobos/ Deimos Fly-by Science (with SEP)	**E1.** Comparative bulk densities of satellites	Satellite shape, morphology, gravity	
			E2. Satellite composition & regolith properties	Satellite mineral composition & thermophysical properties	

Table II: Traceability of Measurement Objectives for Resources, Telecom, and Recon

Programmatic Aspect	Relationship to NASA Goals	Science or Exploration Objective	Investigation	Measurable or Required Quantity
Resource Finding & SKGs	Water resources (ISRU), Civil Engineering Priorities	**RS-A.** Ground Ice	**A1.** Detection of very shallow water ice	Identification of regions with water ice present within 10 m of the surface
			A2. Characterize material properties & thickness of dry overburden	Identification of regions where depth of dry overburden is <2 m, and estimation of material thickness & consolidation
		RS-B. Hydrated Minerals	Characterization of water in hydrated minerals	Identification of hydrous minerals exposed at the surface & and estimation of their subsurface distribution
		RS-C. Mineral Resources & Geotechnical Properties	Minerals & surface properties	Mineral abundances & particle sizes; slopes; surface texture, & load bearing strength
	SKGs (atmosphere and moons)	**RS-D.** Characterization of the Martian atmosphere	Enable accurate models of the atmosphere for landing & other such activities	Globally monitor dust, temperature, & wind at all local times & under very dusty conditions
		RS-E. Exploration of the Martian Moons, Phobos & Deimos	**E1.** Shape, morphology, gravity	Gravity field, density, & internal structure of the moons
			E2. Surface composition/properties & resource potential	Identification of geologic units on Phobos & determine regolith physical properties and composition within those units
Telecom & Recon	Program Requirement	Telecom / Relay	Commands/Data Return	Daily contact
		Site Certification	Surface Hazards	Imaging with <1 m spatial resolution (≤30 cm/pixel)
	Program Continuation	Site Characterization & Identification	Potential for Future Discovery or Exploitation	Morphology, mineral composition & abundances, particle sizes, induration, geologic context
		Critical Event Environment & Coverage	Atmospheric Environment at Season of Arrival	Atmospheric density & winds as a function of season & time of day
				Weather
	Possible Program Enhancement	Planning Rover Traverses from Orbital data alone	Hazard Detection	Ultra-high resolution imaging to plan rover traverses before landing from orbital data alone
			Surface Target Identification	High-resolution spectral imaging to identify targets of interest

LEGEND for Tables I-II: Must Have | High Priority | Lower Priority/Accommodation Risk

III. Measurement Approaches

NEX-SAG was chartered to identify instrument concepts that served as "existence proofs" for achieving the measurement objectives needed to address the compelling reconnaissance, resource, and science objectives and that could be available in the development time frame of a 2022 orbiter. This also provided a conceptual mission payload for use by the Orbiter Study Team to ascertain which spacecraft options and payload suites may be technically feasible and to obtain a rough-order-of-magnitude estimate of the cost of such a mission. Once the mission concept has matured, a future Resources/Science Definition Team (RSDT or equivalent) would define a definitive payload or suite of payloads.

Basic Payload Capabilities Needed

NEX-SAG considered various measurement approaches to address the reconnaissance, resource, and science objectives discussed above. The mapping of science, resource, and reconnaissance objectives into specific measurement objectives is shown in the Traceability Matrices (Tables I & II). In assessing the technical capabilities required to meet these objectives, NEX-SAG identified instrument proofs-of-concept, which are discussed in the following sections, along with key measurement attributes.

Imaging

Imaging at HiRISE resolution (~30 cm/pixel; ideally with 10-15 cm/pixel) is needed for reconnaissance and addresses a number of the compelling resource and science objectives. HiRISE has only covered 2% of Mars at its nominal high resolution but these images have been used in a wide range of studies, and new discoveries continue to appear as its temporal baseline extends. For many features, including RSL, change detection requires repeat-pass visible wavelength imaging with intervals <100 days, and a high-SNR camera with at least two colors that resolves 1-m features (3-pixel scale). High-resolution stereo topographic imaging has been used to measure distances between layers and trace them, e.g., across the polar caps and assemble the stratigraphic (climatic) record. Furthermore, the potential landing sites for future missions will change with discoveries over the next decade. Higher-resolution imaging could aid several of the resource and science objectives, as well as reconnaissance. Given recent technological advances and the value to be gained, a higher-resolution optical imaging system should be considered.

A small weather camera with low spatial resolution (~1 km/pixel) but a wide field of view would extend almost 20 years of daily global coverage of the Mars weather—started in 1998 with Mars Global Surveyor and continued by MRO MARCI. Augmented with a few well-chosen SWIR channels, such a camera would also provide daily coverage of surface frosts. However, imaging at this resolution would be marginal for detecting new impact craters.

Radar Imaging/Sounding

The NEX-SAG identified polarimetric imaging synthetic aperture radar (PSAR) as a technique to map shallow (<10 m), relatively pure ground ice. Polarimetry (at a minimum, dual circular polarizations, with full polarimetry preferred) is critical so that the coherent backscatter effect from pure ice can be observed – for example high circular polarization ratios observed at the poles of Mercury led to the discovery of ice deposits (Harmon et al., 1994). Such a radar would provide short wavelength imaging coverage, similar to what has been obtained through ground-based polarimetric radar imaging of the Moon, Venus, and Mars, and the Lunar Reconnaissance Orbiter Mini-RF instrument. Unlike the current Mars radars MARSIS and SHARAD, a PSAR would produce imaging as its first order product (instead of sounding profiles), and would have much higher spatial resolution (<15 m versus several hundreds of meters). A PSAR in orbit would have ~100 times better resolution than current Earth-based polarimetric radar imaging, as well as a much higher signal-to-noise ratio. High-resolution visible images of ice-related morphologies (e.g., patterned ground) and modeling of measured diurnal thermal characteristics based on ground temperature mapping may help identify areas where shallow ground ice was present, including areas where that ice is not a relatively clean layer of ice, but instead fills the subsurface pores. The presence of such pore-filling ice, even at relatively high volume fractions in a regolith, is not readily confirmed with radar in the absence of other data.

A radar sensor operated as a sounder differs from the side-looking, polarimetric "imaging" radar (PSAR) discussed above for ground ice and RSL surveys. In the imaging mode, the radar beam points to one side of the spacecraft, and uses the along-track motion to produce a fine spatial resolution product from Doppler processing (e.g., Magellan mapping of Venus). Polarimetric measurements are needed for ice layer and brine detection. In the sounding radar, the beam is pointed toward the nadir, with the signal bandwidth increased to obtain a finer time-delay resolution, and thus better vertical spatial resolution, in the target material (e.g., SHARAD observations of the PLD). This aids characterization of ground-ice overburden and polar layering (see next paragraph). When sounding, a single received polarization is typically used, somewhat offsetting the higher data rate created by the enhanced bandwidth. For PSAR, a sounding mode would most likely require a roll of the spacecraft to bring the beam toward the nadir

A SAR system in a broad-band nadir sounding mode or a radar sounder could produce a data product similar to MRO SHARAD but with higher vertical resolution and near-surface sensitivity. Radar sounding could map the thickness and volume of CO_2 deposits at 10-50 m depths, shallower than what can be observed by the SHARAD radar, and measure their thickness at sub-meter scales as well as their volume. It is also possible that a SAR system in a wide-bandwidth nadir sounding mode could reveal seasonal changes in layering at vertical resolutions that are much finer (<1 m) than those provided by SHARAD. A sounding mode could map layering in the upper 50-100 m of the polar cap at vertical resolutions of tens of centimeters, a resolution not achievable by SHARAD or MARSIS but relevant to recent polar evolution.

Infrared Mappers

Mineral mapping for both resources and science requires improved spatial resolution over current capabilities, with a goal of going from the present CRISM ~18 m/pixel to ~6 m/pixel for a short-wave IR mapper.

Multiband thermal IR mapping (e.g., Mars Odyssey THEMIS) has provided ~100 m/pixel coverage of much of Mars. Improvement to resolutions <30 m/pixel or better would be needed to make a significant advance. For many applications, both to fill SKGs and to gain further constraints on RSL, coverage of the diurnal cycle is a mission requirement. Temperature mapping at ≥3 times of day (pre-dawn, mid-day, late day), over a broad range of seasons, may detect pore ice within the uppermost meter(s) of regolith.

Atmospheric Sounders

Using longer wavelengths, as shown by microwave/sub-mm sounders flown in Earth orbit, would be a major advance for atmospheric SKGs and science objectives. Rosetta pioneered use of a microwave radiometer in deep space. Such an instrument approach could provide the first direct measurement of winds across the Martian globe. An additional major advance would be the retrieval of atmospheric temperatures with good precision even in a dusty atmosphere. The use of SEP allows consideration of active instruments, such as a Doppler wind lidar, surface composition lidar, or swath imaging altimeters. The ones flown on aircraft for Earth or advocated for observing tropospheric winds from space are massive, but these may not be reasonable analogues for systems applicable to Mars. While there appear to be viable or rapidly maturing alternatives, the challenge is assessing whether these devices fit within the overall mission capabilities of mass, power, and cost for development of an orbiter to launch in 2022.

Another new measurement objective would be acquiring vertical profiles of water vapor with daily sampling over much of the planet. Presently, we have only column abundances globally and only at a few local times of day. Both thermal IR and longer wave (sub-mm and microwave) sounders can achieve this. Such vapor profiles would aid investigation of water sources for RSL and could trace water vapor to constrain transport. Finally, aerosol dust and ice profiles are needed, both to further understanding of the dust cycle and to provide inputs to, and validation of, models that are increasingly relied upon to interpret observed phenomena and to provide environmental constraints. A thermal IR sounder would be needed for the aerosol profile measurement.

Instrument "Proof of Concept" Summary

Tables III & IV highlight the applicability of these various instrumental "proof of concepts" to the measurement objectives outlined in Tables I & II, respectively. Also identified are the measurements that need to be made at different times of day or that require near-nadir viewing of the polar regions. (In the tables, "nadir polar coverage" means targeted, on-planet observations over the polar regions within spacecraft roll limits, that preserve high-spatial resolution.) As described earlier, SEP-class spacecraft, with their large solar arrays provide the mass and power in a fuel-efficient way to host and operate these new capabilities in suitable orbits.

Other Potential Instrument Concepts

NEX-SAG is mindful that the new capabilities introduced by the use of SEP for a Mars orbiter are still to be explored, and that advances in technology for planetary missions (with many cross-overs from Earth science) can be more rapid than expected. There may well be other instrument approaches to the needed measurement objectives and they should be considered in future deliberations.

NEX-SAG looked at the following possibilities:

- Ultra-high-resolution optical imaging (~5 cm/pixel) has great promise for science, resources, and reconnaissance objectives. This is the resolution that bridges the gap between the state of knowledge from orbital images, and knowledge from rover and landed platforms. The challenges are for the size and mass of the optics and the demands on the spacecraft for exceptional pointing and stability. Even if technically feasible, the resources required could unacceptably impact achieving other high-priority resource and science objectives. To achieve reasonable coverage would also require the ability to return much more data than even the advanced telecommunications being considered for 2022.

- High-spatial-resolution neutron spectroscopy could detect pore-filling ice (hydrogen) not detectable with polarimetric synthetic aperture radar. However, current technology provides spatial resolutions (e.g., many tens of km) much larger than those desired, and comes with interpretation challenges due to thermal neutrons.

- A Doppler wind lidar, recording active pulses reflected off atmospheric aerosols (abundant in the Mars atmosphere), could yield more precise wind measurements much lower in the atmosphere, while the sub-mm/microwave concept works better higher in the atmosphere, where the wind maxima (jets) are located. Amongst other benefits, this would better constrain models of exchange processes at the surface interface. Possibly a channel could be added to profile atmospheric water vapor. The Earth-analogue versions of this instrument type considered by NEX-SAG were quite massive, but Mars, with its more abundant aerosols, may be an easier target.

- Measuring seasonal changes in frosts could be achieved with a surface compositional lidar with carefully chosen wavelengths or bands (at least 2 bands for each ice absorption). Such a lidar could be used to map at high spatial resolution the presence of surface CO_2-ice and water-ice frosts, with the advantage that such an active optical system could operate at night, allowing coverage of broader areas and times (e.g., in the polar night). A lidar could also yield measurements of along-track topography to assist in understanding the role of terrain in forming microclimates for frost deposition, and perhaps to monitor the growth and thickness of seasonal CO_2 deposits (water ice changes being likely too thin to detect by this method). However, information available to NEX-SAG regarding the lidar systems (e.g., as flown on aircraft systems) suggested that the orbital lidar could be quite large in volume and mass.

Table III: Mapping Measurement Requirements to Instrument Type/Proof-of-Concept for Science

Investigation	***Required Measurements (from Table I)***	Imaging	PSAR Radar	SWIR Mapper	Thermal-IR Mapper	Wide-Angle Camera	Sub-mm: T, wind, water (v)	Thermal-IR Sounder	Time-of-day Coverage	Nadir Polar Coverage
S-A1	Extent & volume of water ice in non-polar regions	B	T		T				✓	✓
	Extent & Volume of buried CO_2 ice in the polar caps	B	T	B	B					✓
	Shallow subsurface structure of polar cap & layered terrain (PLDs)	B	T							✓
	Improved mapping of cap morphology, structure, & composition - as a function of season	T		B	B					✓
S-A2	Seasonal mapping of surface water & CO_2 frost	B		T	T	T			✓	✓
	Polar Radiative Balance			B	T		B	T	✓	✓
	Polar Atmospheric Environment: water vapor, temperature, wind, clouds				B	B	T	T	✓	✓
S-B1	Fine scale morphology as a function of season & time of day	T							✓	
	Mineralogy, hydration state, & surface temperature	B	B	T	T				✓	
	Water vapor changes in lowermost atmosphere						B		✓	
S-B2	Sediment flux in key locales: including dunes, gullies, dust streaks	T								
S-C1	Vertical profiles of horizontal wind components & T(p) with good precision even in dusty atmosphere;						T		✓	✓
S-C2	Vertical profiles of aerosol (dust & ice), & water vapor						T	T	✓	✓
S-C3	Daily global mapping of dust, clouds, & surface frost					T			✓	✓
S-D	Fine-scale composition & morphology in ancient terrain	T	B	T	B					
S-E1	Phobos/Deimos shape, morphology, gravity	T	B			B				
S-E2	Phobos/Deimos surface mineral composition & thermophysical properties			T	T					

Table IV: Mapping Measurement Requirements to Instrument Type/Proof-of-Concept for Resources, SKGs & Reconnaissance

Investigation	***Required Measurements (from Table II)***	Imaging	PSAR Radar	SWIR Mapper	Thermal-IR Mapper	Wide Angle Camera	Sub-mm: T,wind, water (v)	Thermal-IR Sounder	Time-of-day Coverage	Nadir Polar Coverage
RS-A1	Detection of very shallow (<10 m depth) water ice	B	T		B				✓	
RS-A2	Characterize material properties & thickness of dry overburden	B	B		T				✓	
RS-B	Characterization of water in hydrated minerals	B		T	B				✓	
RS-C	Mineral abundances and particle sizes; slopes; surface texture, and load bearing strength	T	B	T	T				✓	
RS-D	Globally monitor dust, temperature, and wind at all local times and under very dusty conditions					T	T	T	✔	✔
RS-E1	Gravity field, density, & internal structure of the Phobos and Deimos	T	B			B				
RS-E2	Identification of geologic units on Phobos & determine regolith physical properties and composition within those units	T		T	T					
Reconnaissance	Site Certification: ≤30 cm/pixel resolution required	T								
	Site Characterization: Morphology, mineral composition & abundances, particle sizes, induration, geologic context	T	B	T	T				✓	
	Site Environment: Atmospheric density & winds						T	B	✓	
	Site Environment: Weather					T			✓	

Legend for Tables III-V:	Investigation: S=Science/RS= Resource & SKGs, -# = Objective/Investigation	T = Threshold	B = Baseline (includes Threshold)

IV. Mission Scenarios

Different Orbital Campaigns

There is a natural tension between some of the elements described above with regard to the choice of orbit for a multi-function 2022 Orbiter mission.

- An equatorial to moderately-inclined orbit would allow the orbit to regularly drift through local solar times. For example, an orbit inclination <75° is required to achieve the requested sampling of the diurnal cycle: 2-3 diurnal cycles per season (i.e., a full diurnal cycle approximately every 60 or 90 days). This drift would allow the observation of the surface and atmosphere frequently enough that diurnal <u>and</u> seasonal changes could be separated.
    - Near-equatorial orbits would greatly limit the latitudinal coverage, including those latitudes were ice is most abundant. For that reason inclinations in the 70-75° range are preferred.
    - However, while in these orbits, there will be times of "poor observing" for visual and SWIR imagers, as surface contrasts tend to disappear near noon and there is little sunlight to observe near the terminators. The desired weather camera, which assembles daily global maps from each orbit track, would have a mixture of phase angle effects when part of its field of view is in the dark: the daily global mosaic would have alternating strips that are 12 hours apart rather than a ~2 hour orbital period.
    - High resolution observations of the surface and lower atmosphere at multiple times of day have not been possible before, so observing for more than one Mars year in the lower-inclination, diurnally varying mission phase would be beneficial, to separating diurnal, seasonal and interannual variations. Some of this additional observation could be achieved during the one-year transition phase required by SEP to move into a high-inclination, sun-fixed orbit.
- To achieve the highest-priority polar science objectives, an orbit with inclination above 75° is necessary. From lower-inclination orbits, the polar atmosphere can be observed in limb viewing mode, but the objective of witnessing surface change at high latitude is still not satisfied. To achieve nadir viewing for these objectives requires a near-polar orbit.
    - A sun-fixed orbit (typical of MRO and ODY) is near-polar, but leaves a region stretching ~2.5° around the pole that is not accessible with nadir views (assuming roll limits for the spacecraft comparable to MRO). That area can perhaps be covered during the transition phase.
    - One preferred local time for a sun-fixed orbit, balancing the signal-to-noise and surface illumination contrast, is mid-afternoon (3 a.m./p.m. LMST). This would also enable easy comparison with the data collected by MRO, but is not ideal for observing phenomena like RSL. For that, a fixed time in the mid-morning (~9 a.m./p.m. LMST) may be preferable as RSL are hypothesized to be active in the morning.

SEP provides the capability to combine two such "campaigns", with the corresponding change in orbit, in the same 5-year mission.

In discussions within NEX-SAG and the Orbiter Study Team regarding the order of the two "campaigns", there did not appear to be a strong preference based on orbital mechanics. However, it was recognized that the order of the two campaigns does have implications for when and how one may address the science and resource/SKG objectives. In particular, objectives addressable during the first campaign would be addressed sooner, while the data sets collected during the second campaign could be continued over a much longer period of time if the mission were to be extended.

NEX-SAG discussions about achievement of the Objectives yielded a preference for:

- First going to an orbit with moderate inclination, to observe the surface/atmosphere and at a range of times of day, over at least one full Mars year. Observations over a one-year transition phase would help ensure that characterizations and models of the diurnal variations observed earlier were representative.
- The orbiter would then transition to a sun-fixed polar orbit, preferably with an equator-crossing node in mid-afternoon or mid-morning. A key point is that an optimal time could be chosen on the basis of the earlier campaign characterizing diurnal variations. At least one Mars year would be spent observing in this second orbit, meeting the 5-year mission requirement.
    - One drawback of this orbital phasing is that ground assets (particularly rovers) prefer the relay orbiters to be available at the same time each day and late in the day. If MRO and/or TGO are adequately handling the relay needs of the 2020 Mars Rover, that would be an opportune time to conduct the diurnally varying orbit phase and then transition to an acceptable time for relay from a sun-fixed orbit plane.
- While other sequences are possible, this sequence would allow faster access to data taken at different times of day, providing new insight into RSL and aiding the characterization of surface and subsurface ice at nonpolar latitudes. That information could then aid design of the polar science campaign. The actual decision of exactly which high-inclination orbit to transition into may not have to be made until approaching the end of that first, diurnally varying mission phase.
- If the spacecraft is to return an orbiting container/cache back to Earth vicinity, it would nominally leave at the end of the 5 years in low Mars orbit; the date of that return clearly depends on several factors and could change during the mission based on other circumstances.

FINDING 23*: Accomplishing all the highest-priority science objectives on a single mission will require a phased mission design. For example, investigation of both RSL and volatile cycling processes requires sampling across the full diurnal cycle repeatedly within each Mars season, from a moderately inclined orbit, as well as observations from a high-inclination orbit for polar science.*

Payload Accommodations

It remains to be fully understood whether even a SEP-powered spacecraft has the mass and power resources to accommodate the many instrument types needed to address all the objectives of this multi-function Orbiter mission. (It is clear to NEX-SAG that the proposed chemical-propulsion orbiter class does not.) The Orbiter Study Team continues to assess this issue, which is complicated by the ongoing definition of the capabilities needed for the technical demonstrations and the level of support for inclusion of advanced capabilities. Here NEX-SAG notes some typical payload accommodation issues for instruments that may be selected to achieve the multi-function mission objectives.

Some of the key instrument types require large apertures or sizeable antennas (e.g., PSAR). These compete with the volume and mass needed by, or complicate the design of, the large high-gain-antennas (≥3 m diameter) typically required to return large data volumes from Mars to Earth. The solar arrays that support SEP are also quite large and may block instrument, telecom antenna, or radiator views in some configurations.

Several instruments are likely to need radiators to keep detectors cold and signal-to-noise high (e.g., SWIR mineral mapper and thermal IR sounders), and these need unobstructed views of cold space, which is more complicated when the spacecraft drifts through different times of day. To achieve some objectives (e.g., observing the wind vector) requires multiple or expanded fields of view.

As discussed earlier, increasing instrument spatial resolution means the orbiter must have the pointing precision and stability to enable these instruments to avoid smearing or distortion. This issue is most acute for a finer-than-HiRISE-resolution visible imager.

Longer-wavelength IR instruments may require gimbaling to gain high resolution, in part to compensate for the spacecraft ground-track motion, as CRISM does on MRO. Other instruments may gimbal to use different look directions for specific objectives (e.g., wind or stereo). All such motion—including that of large solar panels and telecom antenna would impact stability for high-resolution imaging and mapping. MRO pauses instrument and solar array gimbaling to achieve adequate HiRISE 30 cm/pixel resolution. On the 2022 orbiter that may disrupt other observing sequences. This is not insurmountable, but for the spacecraft to achieve high stability does require mass (e.g., gimbal size) and can be expensive.

Orbiting at altitudes lower than MRO (~300 km) or "deep-dipping" into the atmosphere as MAVEN does (with periapsis lowered from 150 to 125 km on 4 occasions per year) could improve instrument spatial resolution, but only if the needed pointing stability and precision can be maintained within the denser portion of the atmosphere; the very large solar arrays of a SEP mission, especially one which may have large radar and telecom antennas would seem to preclude lower altitude (< 300 km) operations.

V. Mission Concepts

Based on Tables III and IV above, seven instrument “proof-of-concepts” were identified to address all the functions (telecom and reconnaissance) and objectives (resource prospecting, SKG filling, and science) envisioned for a 2022 orbiter. The number of instrument types is perhaps not as challenging (MRO has six comparable systems) as accommodating multiple antennas and fields of view, including for spacecraft and payload radiators, with a rendezvous and capture subsystem. However, NEX-SAG believes that a SEP-driven spacecraft changes the paradigm, reducing fuel mass and providing greater capabilities for a Mars-centric payload.

Flight of all the desired capabilities (Table V) or the possibility of returning the spacecraft to Earth vicinity may push the mission concept into the more capable SEP systems (Figure 1, Mission Option C). This still seems within technical reach for a 2022 launch. While cost is always an issue, NEX-SAG notes that international partners could provide several of the desired spacecraft subsystems and instrumental capabilities. Finally, within NASA, the multi-function mission envisioned here is, by design, addressing high priority objectives for both planetary science and for human exploration. Given the synergies between objectives, this mission would enable both directorates to move forward in a more cost-effective way.

If not all of the remote sensing payload needed to meet the multiple functions posed for this orbiter can be flown, there are options that could address a subset of those functions. Possible focused payloads are listed in Table V, which uses mass as a metric for spacecraft accommodation capability and for cost. The payload mass estimates in Table V for the various instrument concepts are of course rough estimates only, used to envision what might fit into which mission option. Note that the imaging needed for basic reconnaissance is included in all options and mass estimates; relay and rendezvous/capture mechanisms are not (which accounts for the Mission Options mass limits shown at the bottom of Table V). For comparison, MRO HiRISE (imager), CRISM (imaging spectrometer), MARCI (wide angle camera), and MCS (IR atmospheric sounder) had masses of 65, 33, 1 and 9 kg, respectively, totaling 108 kg; and ODY THEMIS (thermal IR imaging radiometer and push-frame context camera) weighed 11 kg. The numbers in Table V assumed less mass for a HiRISE-class imager based on technical advances in light-weighting of mirrors (considered, but not implemented, by MRO). The sub-mm/microwave sounder has not flown in this configuration, but has been advocated in a number of Discovery and Scout proposals (e.g., MARVEL) and European missions, as well as NASA and joint ESA-NASA studies (Zurek et al., 2011). Perhaps the most difficult item to estimate is the polarimetric radar because of different possible antenna configurations.

Based on mass alone, two things are apparent: *1)* the full-up mission is at the top of the Option B missions being studied or is in the more capable Option C case; and *2)* the bi-propellant class (Figure 1, Mission Option A) could indeed carry only a basic reconnaissance imager similar to MRO HiRISE plus an improved telecommunications package and a rendezvous and capture demonstration package (but no return to Earth). In this case, advanced telecom and no competition from other instruments should enable a signification expansion of sub-meter spatial resolution coverage (10-20% of Mars, compared to the present <3%). Higher resolution (10-15 cm/pixel) would limit that coverage again to MRO capability, unless the downlink capability were enhanced by a factor greater than 10.

Focusing on ground ice characterization for science and resource prospecting is within the range of the Option B SEP missions. Its priority for human exploration rests on the acceptability of mid-latitude ground ice as a resource accessible at a reasonable depth.

A focus on RSL and Environmental Transition objectives (i.e., current and ancient water) requires capabilities probably at the high end of the Option B SEP mission, and would address a different synergistic subset of science and resource prospecting by emphasizing hydrated mineral characterization.

A focus on atmospheric science and SKG-filling activities is well within the Option B mission capabilities. While addressing the SKG objectives, an atmosphere-focused mission would not address the resource objective of prospecting for water.

Only a SEP mission could provide significant observations of the Martian moons; this is possible within the Class B scope.

Class C would be needed to provide the capability for possible return of an actual cache of Mars samples to Earth vicinity (not shown in Table V).

Note that the mass required to address more than one or even all of these mission concepts is much less than the sum of the masses cited for each one of the alternate payloads. This is because there is tremendous synergy between instrument types needed to achieve objectives within the science area and between science and the resource prospecting/SKG filling activities. As has been described, most instruments address multiple objectives.

NEX-SAG did not prioritize between these objectives, as the need to do this depends critically on the funding available and the objectives of the funding directorates. This mission scope and the associated specific capabilities are what is needed by a future RSDT (or equivalent) to refine the technical capabilities needed to address specific mission objectives and, if needed, to choose amongst mission concepts, like those listed in Table V.

The greatest challenge of combining possible objectives may be trying to merge the actual return of an orbiting sample cache to Earth vicinity and the science/resource objectives advocated here for Mars. In the end that may be too much for a single spacecraft. However, the use of ever-more capable SEP has opened up these new possibilities worthy of study.

> **Finding 24:** ***Accomplishing a substantial subset of the desired measurement objectives (described above) will require a spacecraft and payload more capable than MAVEN/MRO. Only a SEP-powered system has the necessary resources (payload and mass) to support the full complement or a majority of the payload measurement approaches and the orbital configurations that NEX-SAG finds necessary to meet the multi-function mission objectives.***

Daughter Spacecraft

Given the somewhat ambitious payload suggested above, it is not clear whether there would be any “extra” mass on an orbiter using commercial SEP for accommodation of additional investigations. However, it may be possible, especially with the use of the advanced (ARRM) SEP system. If there is “extra” mass available, this could be used to accommodate advanced, but more resource-demanding, enhancements to the presently proposed investigations, or even additional investigations. Possible alternative instrument approaches were discussed above.

An intriguing possibility would be to add a daughter spacecraft – small spacecraft (e.g., cubesats or probes) carried into Mars orbit by the main spacecraft and dependent upon it for relay of acquired data back to Earth. The use of SEP may enable leaving this “daughtercraft” in a different orbit than those chosen for the primary mission.

NEX-SAG does not advocate adding a daughtercraft payload if it were to displace a main payload instrument. Additionally, NEX-SAG notes that placing a key science instrument on a daughtercraft could effectively downgrade the associated measurement investigation if the craft has a shorter lifetime (e.g., single string subsystems), a reduced communications bandwidth, and a less flexible orbit than for the main spacecraft.

If able to be accommodated, a daughtercraft could demonstrate new capabilities (e.g., telecommunications relay from areostationary orbit or dedicated relay to a single surface asset) or add new science capabilities (e.g., spacecraft-to-spacecraft occultations, gravity measurements, low altitude probes, simple Mars surface packages, small aerial platforms, Mars moon landers, arrays of microsatellites, etc.). Recent major advances in the capabilities of cubesats and microsatellites (e.g., miniaturization, deployable structures, etc.) may support a range of science investigations that could be accomplished via small, autonomous platforms. Daughtercraft could be selected competitively and possibly be PI-led.

> **FINDING 25***: In the event of “extra” spacecraft capability, an openly competed call promoting the submission of daughtercraft concepts within defined constraints would expand the opportunities for the scientific and exploration communities and promote opportunities for innovative Mars system exploration concepts. This should not displace the capabilities and funding needed to accomplish the strategic objectives proposed by NEX-SAG for a 2022 Orbiter.*

International Participation

> **Finding 26***: NEX-SAG notes that there are many possible contributions by international partners, both for spacecraft subsystems and for the payload elements needed to meet the recommended mission measurement objectives.*

Such collaboration on previous missions for many of the desired instrument types has successfully expanded what has been accomplished in Earth orbit and various planetary missions and could do so again for the 2022 Orbiter. Appropriate funding by several NASA mission directorates and international partners could make it possible to exploit the full capabilities of this SEP-driven 2022 Orbiter. In addition to being beneficial for the 2022 mission, such cross-directorate and international collaboration could provide a critical step forward to the collaboration that will be ultimately needed for the longer-term exploration of Mars by humans operating on its surface.

Table V: Mission Concepts

Mission Concept	***Investigations Addressed (See Tables III-IV)***	Imaging	PSAR (Radar)	SWIR Mapper	Thermal-IR Mapper	Wide Angle Camera	Sub-mm: T, wind, water (v)	Thermal-IR Sounder	Time-of-day Coverage	Nadir Polar Coverage	Estimated Payload Mass [kg] for Threshold (and Baseline)
ALL	**All Functions and Objectives**	T	T	T	T	T	T	T	✓	✓	225
Ground Ice	Detection of very shallow ice, structure, and overburden: RS-A1, RS-A2, S-A1; baseline adds S-A2 (partial: frost)	T	T	B	T	B			✓	✓	130 (175)
Signs of current and ancient water	RSL & Environmental Transitions (mineralogy & stratigraphy): RS-B, RS-C, S-B1, S-B2, S-D	T	B	T	T		B		✔		105 (210)
Atmosphere Science & SKGs +Recon	Current Martian Atmosphere studies and global monitoring: RS-D, S-C1, S-C2, S-C3, S-B2 + Reconnaissance (partial: certify sites)	T				T	T	T	✓	✓	105 (105)
Phobos-Deimos (SEP only)	Identify geologic units and constrain densities of Mars moons: RS-E, S-E	T	B	T	T	B					105 (175)
Basic Reconnaissance	Reconnaissance (threshold: Certification and S-B2; baseline adds characterization of new sites and atmospheric conditions)	T	B	B	B	B	B (one of these)		✓		50 (185 or 215)
	Estimated instrument mass [kg]	50	65	40	15	5	40	10			

Note: Representative instrument payload mass limits for Mission Options A, B, C are 80, 200 & >200 kg (see Mission Options).

Legend for Tables III-V:	Investigation: S=Science/RS= Resource & SKGs, -N# = Objective/Investigation	T = Threshold	B = Baseline (includes Threshold)

VI. Traceability

Two types of traceability are shown in this report:

- The NEX-SAG members defined and evaluated the high-priority Science, Resource, and Programmatic Objectives based on instructions in the charter, discussions with Mars Science and Resource community members (including ICE-WG), and review of the Decadal Goals (NRC, 2011) and MEPAG Goals Document (MEPAG, 2015). Tables I and II shows the connection between the NEX-SAG defined Objectives and the Decadal Survey. Table VI shows the traceability to the MEPAG Goals (MEPAG, 2015), including input from ICE-WG regarding the mapping to Goal IV. Further detail on the traceability of SKGs to Goal IV is given in Appendix 4.
- After defining the high-priority Science, Resource, and Programmatic Objectives, the NEX-SAG members traced these Objectives into investigations, then measurement requirements. This is described in Sections I and II and then summarized in Tables I and II. Tables III and IV then trace the measurement requirements for Science, Resources, and Reconnaissance to instrument type (proof-of-concepts). A collection of possible mission concepts is presented in Table V.

Table VI: Traceability to MEPAG Goals

MEPAG Goals: Listed in Appendix 3	**Goal I:** Life	**Goal II:** Climate	**Goal III:** Geology & Geophysics	**Goal IV:** Prepar. for Human Explor. (map to SKGs, Appendix 4)
NEX-SAG Science Objectives				
S-A. Distribution & Origin of Ice Reservoirs	A1.1, A1.2, B1.2, B1.3, B1.5	A4.2, B2.1, B3.1	A1.1, A1.4, A3.1, A3.2, A3.3	
S-B. Dynamic Surface Processes on Modern Mars	B1.1, B1.2	A4.1	A1.1, A3.2, A3.3	
S-C. Dynamic Processes in Current Martian Atmosphere	B1.1, B1.2	A1.1, A1.2, A3.1, A3.2		
S-D. Geologic Evidence for Environmental Transitions	A1.1, A1.2, A1.3, A1.4	B2.1, C2.1	A1.2, A2.3, A3.1, B1.1	
S-E. Phobos/ Deimos Fly-by Science (with SEP)			C1.1, C1.2, C2.2	
NEX-SAG Resource and SKG Objectives				
RS-A. Water Resources: Ground Ice				B3.1, D1.1
RS-B. Water Resources: Hydrated Minerals				D1.1
RS-C. Mineral Resources & Geotechnical Properties				B5.1, B5.2
RS-D. Exploration of the Martian Moons				C1.1, C1.2, C1.3
RS-E. Characterization of the Martian Atmosphere				A1.1, A1.2, A1.3, B1.1, B1.3, B7.3

VII. Summary

A 2022 Mars Orbiter utilizing Solar Electric Propulsion (SEP) and advanced telecom in a 5-year mission after the orbiter spirals in to low Mars orbit, could provide exciting new science and resource identification in addition to programmatic functions such as telecommunications relay, critical event coverage, and surface reconnaissance. The high degree of overlap between objectives for resource prospecting and high-priority science (e.g., ground ice location) enables selection of instruments that individually address multiple needs and that collectively provide synergistic observations. Such a multi-function orbiter mission appears feasible only with SEP and is greatly leveraged by advanced telecommunications.

In summary, the NEX-SAG finds that the multi-functional mission envisioned here would make major advances in our scientific understanding of Mars and its climate evolution, and would provide a major step forward in identifying resources for future exploration by humans on Mars and the Martian moons. It would do this while also providing the reliable telecommunications and reconnaissance needed by the missions that would follow the 2020 Mars Rover.

Appendix 1. Mars Next Orbiter Science Analysis Group (NEX-SAG) Charter

Introduction

NASA has requested MEPAG to prepare an analysis of the science objectives and science measurement capabilities that may be implemented by a Mars orbiter that could be launched in the 2022/24 timeframe. MEPAG has indicated that it would conduct this analysis through formation of a Next Orbiter Science Analysis Group (NEX-SAG). This activity is being co-chartered by SMD/MEP and by HEOMD.

Background

NASA Headquarters is looking at possible flight programs for launch to Mars after the proposed 2020 Mars rover mission currently in development. One option to be considered is the flight in the early 2020's of an orbiter whose capabilities could address objectives in the following areas:

- Replenishment of the telecommunications and reconnaissance infrastructure presently provided by Mars Odyssey and Mars Reconnaissance Orbiter.
- Scientific and technical progress on the NRC Planetary Science Decadal Survey priorities and/or follow up on new discoveries.
- Location and quantification of *in situ* resources for utilization by future robotic and human surface-based missions.
- Acquisition of data to address Strategic Knowledge Gaps (SKGs).

The missions to follow this proposed orbiter are not yet defined, but information from this orbiter will likely support both robotic and human exploration missions. Thus, aspects of the above functions are of interest to both HEOMD and SMD and may involve emerging technologies being developed within these directorates and by STMD. There is, as yet, no baseline concept of the mission. Thus, a range of options with regard to capability and cost will be provided for examination. Separate working groups are defining landing site criteria and scientific objectives for human exploration missions in parallel with this study. Preliminary results from these studies will be provided mid-term to this study group.

Charter

NEX-SAG is directed as follows:

a) Because of its criticality, a telecommunications relay system is required to send commands to, and return data from, Mars assets, particularly during Entry, Descent, and Landing (EDL) and subsequent operation on the surface of Mars. This relay capability shall be included in all mission scenarios considered, and the mission scenario shall be capable of supporting each of several Mars surface assets. NEX-SAG shall begin by assuming that the relay capability required will be at least as capable as MRO and that mission scenarios are such that this capability can be utilized in a timely way.

b) Again because of its criticality, remote sensing capability essential to certifying the safety of candidate landing sites for future missions shall also be included in all mission scenarios considered. These landing sites would be for missions launching after 2020. Initially, NEX-SAG shall assume that the landing site safety requirements are similar to those specified for MSL and the 2020 Mars rover and that the remote sensing capabilities required are equivalent to, or better than, those currently provided by MRO.

c) NEX-SAG shall update its considerations of the above programmatic needs when provided with preliminary results from studies by parallel study groups chartered by NASA Headquarters; such information is expected by early June.

d) A spacecraft operational lifetime of at least 5 years in Mars orbit shall be assumed.

e) Assessments of scientific priority shall assume that the InSight, ExoMars Trace Gas Orbiter (TGO), and 2020 Mars missions will be successful.

f) The range of capabilities for specific mission options will be provided as study targets. These represent a range of cost envelopes covering both the MAVEN (Scout Class) and MRO (Strategic, directed) missions. For the purposes of this study, assume that the mission will be a directed strategic mission. The possibility of reasonable contributions by non-SMD Directorates or by International Partners can be considered. Further, consider the possible use of two new technical capabilities:

   i. Improved telecommunications rates for downlink; and

   ii. Solar electric propulsion (SEP), which has the potential to provide fuel-friendly orbit changes and unprecedented power for payloads once in orbit. Note that SEP requires spiraling into Mars orbit past--but not necessarily in the orbital planes of--the Mars moons, which could be targets of opportunity.

Specific Tasks

1) Science. Identify and prioritize science objectives within each mission option. Priorities shall reflect the degree to which the objectives address the NRC Planetary Science Decadal Survey priorities (e.g., sample return) and the likelihood that measurement approaches exist and can be implemented within the capabilities and resources of a given mission option. New discoveries may also motivate specific objectives, but a strong rationale for these is required. An example of this is the phenomenon of Recurring Slope Lineae (RSL) that suggest intermittent liquid (briny) water activity on Mars today.

2) Exploration Resources. Identify remote sensing capabilities that can locate, characterize, and—where possible—quantify resources that may be needed to support exploration by humans on the surface of Mars. Initially assume that the required information is the presence of water ice or hydrates at the surface or in the near subsurface (< ~10 m depth). Study groups working in parallel will provide confirmation, updates, or changes to this assumption by early June.

3) Measurement Approaches. For both (1) and (2), identify measurement approaches needed to meet scientific objectives and to assist resource location and quantification. Identify synergies between these and/or the capabilities needed to conduct basic reconnaissance for landing site safety and access.

4) Mission Scenarios. Identify mission scenarios consisting of mission timelines, orbit parameters, and payload combinations for various mission options within the given range of mission concepts/resources,

5) Traceability. For each key mission scenario, do the following:
    a. Analyze the degree of alignment of different payload combinations with the NRC Planetary Science Decadal Survey, taking into account recent discoveries, and with the (revised) MEPAG Goals document.
    b. Identify which HEOMD Strategic Knowledge Gaps (SKGs) are addressed and to what degree.
    c. Provide the rationale for all expressions of priority of options and objectives.

Methods

- NEX-SAG will conduct their business primarily via telecons, e-mail, and/or web-based processes. Up to two face-to-face meetings may be accommodated, if needed.
- When added expertise is needed, NEX-SAG will request a briefing from a recognized subject-matter-expert.
- The Advanced Studies and Formulation element of the Mars Program Office (MPO) will support the NEX-SAG study.
- The MPO's Science Office will provide logistical support.

Schedule

- NEX-SAG will form and begin its discussions as soon as possible.
- A midterm status check by co-conveners Michael Meyer and Ben Bussey, and MEPAG Chair Lisa Pratt is requested by end-of-June, 2015.
- A draft text report to be reviewed by the MEPAG Executive Committee and by HEOMD and SMD/MEP is requested by mid-September.
- A final report, text formatted, and a PPT briefing package to SMD/MEP and HEOMD is requested by 1 November, 2015.

Report Posting

- After the report has been accepted by MEPAG and NASA management, it will be posted on a publicly accessible website.
- The report will not contain any material that is ITAR-sensitive.

Related References

- Beaty, D. W., M. H. Carr et al., (2012): *Analysis of Strategic Knowledge Gaps Associated with Potential Human Missions to the Martian System: Final report of the Precursor Strategy Analysis Group* (P-SAG), 72 pp., posted July 2012 on the MEPAG Website*.
- Calvin, W. et al., (2007): *Report from the 2013 Mars Science Orbiter (MSO) Second Science Analysis Group*, 72 pp., posted June 2007 on the MEPAG Website*.
- Rummel, J., D. Beaty et al., (2014): *Special Regions Science Analysis Group* (SR-SAG2), *Astrobiology,* posted November 2014 on the MEPAG Website*.
- *Mars Science Goals, Objectives, Investigations, and Priorities: 2015 Version,* V. E. Hamilton et al., MEPAG*
- *Vision and Voyages* for Planetary Science in the Decade 2013-2022 (2011).

  * SAGs and activity supported by the Mars Exploration Program Analysis Group (MEPAG); see http://mepag.jpl.nasa.gov/reports/index.html

Chartered by:

Ben Bussey, *Chief Exploration Scientist*, HEOMD, NASA HQ
Michael Meyer, *Lead Scientist for Mars Exploration*, MEP/SMD, NASA HQ

Charter accepted by: Lisa Pratt, Chair, MEPAG Chair, April 2015

Concurred by: James Watzin, Mars Program Director, MEP/SMD, NASA HQ.

Appendix 2. All Findings

Finding # / page	Finding text
1/ p10	NEX-SAG finds that a demonstration of rendezvous and capture or actual return of a retrieved container/cache to Earth vicinity would likely require SEP capability, especially if other high-priority resource and science objectives are to be pursued. Return of an actual cache of Mars samples would fulfill the Decadal Survey's highest flagship priority.
2 / p11	NEX-SAG finds that an orbiter launched in 2022 could be needed to provide critical support for the 2020 Mars rover and would help accelerate both potential sample return and preparations for human missions to Mars. A 2022 launch would also provide opportunities for inter-comparison and synergistic observations with existing orbiters, nearing their end-of-life.
I. Science	
3 / p15	Measurements that could determine the location, thickness, concentration, and depth of buried ground ice – as well as the chemistry of associated mineral alteration and salts – are important for understanding the current climate and past climate cycles on Mars.
4 / p15	Measuring the precise volume of the recently-discovered polar CO_2 ice reservoirs would better constrain atmospheric density during prior epochs, when obliquity cycle variations could have sublimated the current or similar buried CO_2 ice deposits and enabled liquid water to be stable for longer periods over more of the planet.
5 / p17	Knowing the timing of geologically recent climate variations is fundamentally important to understanding Mars. Measurements of the polar layers and the seasonal and annual evolution of near-surface layers are needed to understand the evolution of the poles and the formation of lower latitude surface and subsurface ice deposits.
6 / p17	Measurements over the diurnal cycle at sub-seasonal timescales are necessary to understand the recent climate history of Mars. Formation of snow and frost are highly sensitive to temperature change, as is volatile transport through the atmosphere. Characterizing the cumulative effect of these diurnally varying processes may be key to understanding the overall exchange between the, poles and non-polar latitudes.
7 / p18	Recurring Slope Lineae (RSL) are a significant discovery since the Decadal Survey. Their morphology and spectral properties are most consistent with flow on Mars today of liquid water, enabled by deliquescent salts or some other process. Understanding RSL processes and sources requires seasonal measurements of their morphology, chemistry, and temperature at high spatial resolution and as a function of time of day.
8 / p20	Continued monitoring of dynamic processes in sand dunes, ripples, dust devils and localized regions of high dust loading will help in understanding aeolian volumetric sediment transport, near-surface convection, dust lifting, and dust storm initiation. Repeat imaging of dynamic surface changes, including gullies,

	will constrain the role of volatiles and sediment transport processes.
9 / p21	Observation of wind velocity is the single most valuable new measurement that can be made to advance knowledge of atmospheric dynamic processes. Near-simultaneous observations of atmospheric wind velocities, temperatures, aerosols, and water vapor with global coverage are required to properly understand the complex interactions that define the current climate.
10 / p22	Current orbiter remote sensing can provide boundary conditions for modeling exchange between the surface and atmosphere, but cannot achieve the vertical resolution needed for direct determination of fluxes of volatiles, mass and energy close to the surface.
11 / p23	Representative diurnal sampling on a timescale less than a Martian season is required to identify how atmospheric phenomena change with varying solar input and to remove aliasing associated with key measurements such as atmospheric temperatures and winds in the context of thermal tides.
12/ p23	Continued observation of the general atmospheric state is required to evaluate further the degree of interannual variability and the presence of secular trends. A minimum set of daily global visual imaging, atmospheric temperature profiles, and daytime column amounts of dust, water ice, and water vapor is required to maintain the decades-long record begun by MGS, Odyssey, and MRO.
13 / p24	Recent exploration has revealed enormous diversity in secondary mineralogies formed by reaction of liquid water with the ancient crust. Higher spatial resolution and broader wavelength range measurements of stratigraphy, mineralogy, and texture are required to understand environmental settings and biosignature preservation potentials of distinctive aqueous deposits >3.5 Ga in age.
14 / p26	The use of SEP and the payload capabilities needed to address the reconnaissance, resource, and science objectives at Mars allow high-value science observations of Phobos and Deimos necessary to plan future missions to these moons.
II. Resources, Strategic Knowledge Gaps	
15 / p31	A combination of thermal IR mapping and polarimetric imaging radar, especially if augmented with a sounding mode, should be able to detect ice within a few meters of the surface and to estimate the depth and physical character of dry material above it (overburden).
16 / p31	High-spatial-resolution observations in the short-wave IR with sufficient spectral resolution, aided by thermal IR spectral mapping, can identify hydrous minerals exposed at the surface, although with uncertainties in extrapolation to water content at depth. Extrapolating hydration at the optical surface to the subsurface accurately depends on the types of minerals present, dust cover, and the presence of adsorbed water especially at low latitude.
17 / p32	A better understanding of which hydrated minerals can provide a practical resource to support humans on Mars is required, so that prospecting from orbit can be focused appropriately.
18 / p34	NEX-SAG finds that there is strong synergy between the various required

	functions as a single instrument may address one or more of the science objectives and one or more of the resource, and reconnaissance needs. Four particularly strong areas of synergy include: i) the location of ground ice, ii) the characterization of hydrated minerals, iii) the structure and dynamics of the lower atmosphere, and iv) the moons of Mars.
II. Reconnaissance and Telecom	
19 / p34	Improved telecom is required to acquire the higher-spatial resolution data sets needed to make significant progress on key resource and science objectives. A full order of magnitude increase, through systems such as optical communications, would be required to achieve spatial coverage, at these higher-spatial resolutions, beyond a few percent of the planet.
20 / p35	HiRISE-class imaging (~30 cm/pixel) is required for landing site certification for future missions. An improvement to ~10-15-cm resolution would enable significant advances in science, and may be technically feasible so should be considered as resources permit.
21 / p35	Although enhancing for many science objectives and helpful for rover operations planning, NEX-SAG concluded that ultra-high-resolution optical imaging (~5 cm/pixel or better) poses major accommodation challenges.
22 / p36	Identification and characterization of future landing sites should include atmospheric monitoring to improve environmental models, ground ice prospecting, and mineral mapping to characterize potential landing sites in terms of resource access and of scientific regions of interest. Orbital monitoring of dust storms and of surface asset location would aid planning for missions while operating on the surface.
IV. Mission Scenarios and V. Mission Concepts	
23 / p46	Accomplishing all the highest-priority science objectives on a single mission will require a phased mission design. For example, investigation of both RSL and volatile cycling processes requires sampling across the full diurnal cycle repeatedly within each Mars season, from a moderately inclined orbit, as well as observations from a high-inclination orbit for polar science.
24 / p49	Accomplishing a substantial subset of the desired measurement objectives (described above) will require a spacecraft and payload more capable than MAVEN/MRO. Only a SEP-powered system has the necessary resources (payload and mass) to support the full complement or a majority of the payload measurement approaches and the orbital configurations that NEX-SAG finds necessary to meet the multi-function mission objectives.
25 / p50	In the event of “extra” spacecraft capability, an openly competed call promoting the submission of daughtercraft concepts within defined constraints would expand the opportunities for the scientific and exploration community and promote opportunities for innovative Mars system exploration concepts. This should not displace the capabilities and funding needed to accomplish the strategic objectives proposed by NEX-SAG for a 2022 Orbiter.
26 / p50	NEX-SAG notes that there are many possible contributions by international partners, both for spacecraft subsystems and for the payload elements needed to meet the recommended mission measurement objectives.

Appendix 3. MEPAG Goals noted in Traceability/Table VI

Only the MEPAG Investigations noted in Table VI are listed here. The full spreadsheet and the main MEPAG Goals text can be downloaded from: http://mepag.nasa.gov/reports.cfm?expand=science

Objectives	Sub-objectives	Investigations
GOAL I: Determine if Mars ever supported life.		
A. Determine if environments having high potential for prior habitability and preservation of biosignatures contain evidence of past life.	**A1.** Identify environments that were habitable in the past, and characterize conditions and processes that may have influenced the degree or nature of habitability therein.	1. Establish overall geological context.
		2. Constrain prior water availability with respect to duration, extent, and chemical activity.
		3. Constrain prior energy availability with respect to type (e.g., light, specific redox couples), chemical potential (e.g., Gibbs energy yield), & flux.
		4. Constrain prior physicochemical conditions, emphasizing temperature, pH, water activity, and chemical composition.
B. Determine if environments with high potential for current habitability and expression of biosignatures contain evidence of extant life.	**B1.** Identify environments that are presently habitable, and characterize conditions and processes that may influence the nature or degree of habitability therein.	1. Identify areas where liquid water (including brines) presently exists, with emphasis on reservoirs that are relatively extensive in space and time.
		2. Identify areas where liquid water (including brines) may have existed at or near the surface in the relatively recent past including periods of significant different obliquity.
		3. Establish general geological context (such as rock-hosted aquifer or sub-ice reservoir; host rock type).
		5. Assess the variation through time of physical and chemical conditions, (particularly temperature, pH, and fluid composition) in such environments and potential processes responsible for observed variations.
GOAL II: Understand the processes and history of climate on Mars.		
A. Characterize the state of the present climate of Mars' atmosphere and surrounding plasma environment, and the underlying processes, under	**A1.** Constrain the processes that control the present distributions of dust, water, and carbon dioxide in the lower atmosphere, at daily, seasonal and multi-annual timescales.	1. Measure the state and variability of the lower atmosphere from turbulent scales to global scales.
		2. Characterize dust, water vapor, and clouds in the lower atmosphere.

the current orbital configuration.	**A3.** Constrain the processes that control the chemical composition of the atmosphere and surrounding plasma environment.	1. Measure globally the vertical profiles of key chemical species.
		2. Map spatial and temporal variations in the column abundances of species that play important roles in atmospheric chemistry or are transport tracers.
	A4. Constrain the processes by which volatiles and dust exchange between surface and atmospheric reservoirs.	1. Measure the turbulent fluxes of dust and volatiles between surface and atmospheric reservoirs.
		2. Determine how the exchange of volatiles and dust between surface and atmospheric reservoirs has affected the present distribution of surface and subsurface water and CO2 ice.
	B2. Determine the record of the recent past that is expressed in geological and mineralogical features of the polar regions.	1. Map the ice and dust layers of the PLD and determine the absolute ages of the layers.
	B3. Determine the record of the climate of the recent past that is expressed in geological and mineralogical features of low- and mid-latitudes.	1. Identify and map the location, age, and extent of glacial and peri-glacial features and quantify the depth to any remnant glacial ice.
C. Characterize Mars' ancient climate and underlying processes.	**C2.** Find and interpret physical and chemical records of past climates and factors that affect climate.	1. Determine the atmospheric environment required by observed geochemical and geophysical features.
GOAL III: Understand the origin and evolution of Mars as a geological system.		
A. Document the geologic record preserved in the crust and interpret the processes that have created that record.	**A1.** Identify and characterize past and present geologic environments and processes relevant to the crust.	1. Determine the role of water and other processes in the sediment cycle.
		2. Identify the geochemical and mineralogic constituents of crustal materials and the processes that have altered them.
		4. Identify ice-related processes and characterize when and how they have modified the Martian surface.
	A2. Determine the absolute and relative ages of geologic units and events through Martian history.	3. Identify and characterize the distribution, nature, and age relationships of rocks, faults, strata, and other geologic features, via comprehensive and topical geologic mapping.
	A3. Constrain the magnitude, nature, timing, and origin of past planet-wide	1. Identify paleoclimate indicators in the geologic record and estimate the climate timing and duration.

	climate change.	2. Characterize surface-atmosphere interactions as recorded by aeolian, glacial/periglacial, fluvial, lacustrine, chemical and mechanical erosion, cratering and other processes.
		3. Determine the present state, 3-dimensional distribution, and cycling of water on Mars including the cryosphere and possible deep aquifers.
B. Determine the structure, composition, and dynamics of the Martian interior and how it has evolved.	**B1.** Identify and evaluate manifestations of crust-mantle interactions.	1. Determine the types, nature, abundance and interaction of volatiles in the mantle and crust.
C. Determine the manifestations of Mars' evolution as recorded by its moons.	**C1.** Constrain the planetesimal density and type within the Mars neighborhood during Mars formation, as implied by the origin of the Mars moons.	1. Interpret the geologic history of the moons, by identification of geologic units and relationship(s) between them (time-order, weathering, etc.).
		2. Determine composition of rock and regolith on the moons, including elemental and mineralogical compositions.
	C2. Determine the material and impactor flux within the Mars neighborhood, throughout Mars' history, as recorded on the Mars moons.	2. Understand the flux of impactors in the Martian system, as observed outside the Martian atmosphere.
GOAL IV: Prepare for human exploration.		
A. Obtain knowledge of Mars sufficient to design and implement a human mission to Mars orbit with acceptable cost, risk, and performance.	**A1.** Determine the aspects of the atmospheric state that affect aerocapture and aerobreaking for human-scale missions at Mars.	1. At all local times, make long-term (>5 Mars years) observations of the global atmospheric temperature field from 0-80 km.
		2. At all local times, make long-term global measurements of the vertical profile of aerosols between the surface and >60 km.
		3. Make long-term observations of global winds and wind direction at all local times over altitudes 15 to >60 km, and including a planetary scale dust event.
B. Obtain knowledge of Mars sufficient to design and implement a human mission to the Martian surface with	**B1.** Determine the aspects of the atmospheric state that affect Entry, Descent, and Landing (EDL) design, or atmospheric electricity that may pose a risk	1. Globally monitor the dust and aerosol activity, especially large dust events, to create a long-term dust activity climatology (> 10 Mars years) capturing the frequence of all events and defining the duration, horizontal extent, and evolution of extreme events.

acceptable cost, risk, and performance.	to ascent vehicles, ground systems, and human explorers.	3. Make temperature and aerosol profile observations under dusty conditions (including within the core of a global dust storm) from the surface to 20 km (40 km in a great dust storm) with a vertical resolution of <5 km.
	B3. Determine the Martian environmental niches that meet the definition of "Special Region."	1. Map the distribution of both naturally occurring Special Regions, and regions with the potential for spacecraft-induced Special Regions, as defined by COSPAR5.
	B5. Assess landing site-related hazards, including those related to safe landing and safe operations (including trafficability) within the possible area to be accessed by elements of a human mission.	1. Image selected potential landing sites to sufficient resolution to detect and characterize hazards to both landing and trafficability at the scale of the relevant landed systems.
		2. Determine regolith physical properties and structure, gas permeability of the regolith and the chemistry and mineralogy of the regolith, including ice contents.
	B7. Characterize the particulates that could be transported to hardware and infrastructure through the air, and that could affect engineering performance and in situ lifetime.	3. Determine the column abundance and size-frequency distribution, resolved at less than scale height, of dust particles in the Martian atmosphere.
C. Obtain knowledge of Mars sufficient to design and implement a human mission to the surface of either Phobos or Deimos (P/D) with acceptable cost, risk, and performance.	**C1.** Understand the geological, compositional, and geophysical properties of P/D sufficient to establish specific scientific objectives, operations planning, and any potentially available resources.	1. Determine the elemental and mineralogical composition of the surface and near-surface of P/D.
		2. Identify geologic units for science and exploration and materials for future in situ resource utilization operations.
		3. Determine the gravitational field to a sufficiently high degree and order to make inferences regarding the internal structure and mass concentrations of P/D.
D. Obtain knowledge of Mars sufficient to design and implement sustained human presence at the Martian surface with acceptable cost, risk, and performance.	**D1.** Characterize potentially extractable water resources to support ISRU for long-term human needs.	1. Identify a set of candidate water resource deposits that have the potential to be relevant for future human exploration.

Appendix 4. SKGs mapped to the MEPAG Goal IV Investigations noted in Traceability/Table VI

Only the SKGs/GFAs mapping to MEPAG Investigations listed in Table VI are included here. To see the full table/mapping, see the MEPAG Goals document (MEPAG, 2015), Appendix 4. To see the original P-SAG items, see P-SAG (2012).

P-SAG		**2015 MEPAG Goal IV**		
SKG	**GFA**	**Sub-obj.**	**Inv.**	**Priority**
A1. Upper Atmosphere	A1-1. Global temperature field	A1	A1.1	High
	A1-2. Global aerosol profiles and properties		A1.2	High
	A1-3. Global winds and wind profiles		A1.3	Medium
B1. Lower Atmosphere	A1-2. Global aerosol profiles and properties, B1-1. Dust Climatology	B1	B1.1	High
	A1-1. Global temperature field	B1	B1.3	High
B5. Forward Contamination	B5-1. Identify and map special regions	B3	B3.1	High
B7. Landing Site and Hazards	B7-2. Landing site selection	B5	B5.1	High
	B7-1. Regolith physical properties/structure		B5.2	Medium
B4. Dust Effects on Surface Systems	B6-2. Dust column abundances	B7	B7.3	Low
C1. Phobos/Deimos (P/D) Surface Science	C1-1. Surface composition	C1	C1.1	High
B4. Dust Effects on Surface Systems	B6-2. Dust column abundances	B7	C1.2	High
C1. Phobos/Deimos (P/D) Surface Science C2. Phobos/Deimos Surface Operations	C2-2. P/D Gravitational field C2-3. P/D regolith properties	C1	C1.3	Medium
C2. Phobos/Deimos Surface Operations D1. Water Resources	(Mapping of water resources) **NEW**	D1	D1.1	High

Appendix 5. Acronyms used throughout report

2020	2020 Mars rover mission
ARRM	Asteroid Redirect Robotic Mission
CaSSIS	Color and Stereo Surface Imaging (instrument on TGO)
COTS	Commercial, Off The Shelf
CRISM	Compact Reconnaissance Imaging Spectrometer for Mars (instrument on MRO)
HEOMD	NASA Human Exploration and Operations Mission Directorate
HiRISE	High Resolution Imaging Science Experiment (instrument on MRO)
HLS^2	Human Landing Site Selection
HSO-SAG	Human Science Objectives SAG (MEPAG)
ICE-WG	ISRU (*In Situ* Resource Utilization) and Civil Engineering working group (HEOMD)
IR	Infrared
ISRU	*In situ* Resource Utilization
LMST	Local Mean Solar Time
MARCI	Mars Color Imager (instrument on MRO)
MARSIS	Mars Advanced Radar for Subsurface and Ionosphere Sounding (instr. on MEx)
MARVEL	Mars Volcanic Emission and Life Scout (proposed mission)
MAV	Mars Ascent Vehicle
MAVEN	Mars Atmosphere and Volatile Evolution mission
MCS	Mars Climate Sounder (instrument on MRO)
MEPAG	Mars Exploration Program Analysis Group
MEx	Mars Express (ESA mission)
MRO	Mars Reconnaissance Orbiter mission
MSL	Mars Science Laboratory mission
MSR	Mars Sample Return
NEX-SAG	Next Orbiter SAG (MEPAG)
NRC	National Research Council
ODY	Odyssey mission
OSC	Orbiting Sample Cache
PLD	Polar Layered Deposits
(P)SAR	(Polarimetric imaging) SAR
SAG	Science Analysis Group
SAR	Synthetic Aperture Radar
SCAN	Space Communications and Navigation (NASA Program Office)
SEP	Solar Electric Propulsion
SHARAD	Shallow Subsurface Radar (instrument on MRO)
SDT	Science Definition Team
SKG	Strategic Knowledge Gap
SMD	NASA Science Mission Directorate
STMD	NASA Space Technology Mission Directorate
SWIR	Short-wave IR
TGO	2016 ExoMars Trace Gas Orbiter (ESA mission)
UAE	United Arab Emirates (mission: the Emirates Mars Mission orbiter)

Appendix 6. References cited throughout report

Audouard, J., et al. (2014) Water in the Martian regolith from OMEGA/Mars Express,. *J. Geophys. Res. Planets* **119**, 1969-1989, doi:10.1002/2014JE004649.

Bandfield, J.L., A.D. Rogers, C.S. Edwards (2011), The role of aqueous alternation in the formation of Martian soils, *Icarus* **211**(1), 157-171, doi:10.1016/j.icarus.2010.08.028.

Boynton, W.V., et al. (2002), Distribution of hydrogen in the near surface of Mars: Evidence for subsurface ice deposits, *Science 297*(5578), 81-85.

Bramson, A.M., et al. (2015), Widespread excess ice in Arcadia Planitia, Mars, *Geophys. Res. Lett.* **42**(16), 6566-6574, doi:10.1002/2015GL064844.

Bridges, N.T., et al. (2012a) Planet-wide sand motion on Mars. *Geology* **40**, 31-34, doi:10.1130/G32373.1.

Bridges, N.T., F. Ayoub, J.-P. Avouac, S. Leprince, A. Lucas, S. Mattson (2012b) Earth-like sand fluxes on Mars. *Nature* **485**, 339-342, doi:10.1038/nature11022.

Byrne, S., et al. (2009) Distribution of Mid-Latitude Ground Ice on Mars from New Impact Craters, *Science* **325**, 1674-1676, doi:10.1126/science.1175307.

Byrne, S., M.T. Zuber, G.A. Neumann (2008), Interannual and seasonal behavior of Martian residual ice-cap albedo, *Planet. and Space Sci.* **56**, 194-211, doi:10.1016/j.pss.2006.03.018.

Campbell, B.A., et al. (2015), Enhanced radar visualization of structure in the south polar deposits of Mars, *46th LPSC*, Ab. 2366.

Cantor, B.A., P.B. James, W.M. Calvin (2010), MARCI and MOC observations of the atmosphere and surface cap in the north polar region of Mars, *Icarus* **208**(1), 61-81, doi:10.1016/j.icarus.2010.01.032.

Carr, M.H., J.W. Head (2010), Geologic history of Mars, *Earth Planet. Sci. Lett.* **294**, 185-203.

Carr, M. H., J.W. Head (2015), Martian surface/near-surface water inventory: Sources, sinks, and changes with time. *Geophys. Res. Lett.* **42**, 726-732. doi:10.1002/2014GL062464.

Carter, J., F. Poulet, J.-P. Bibring, N. Mangold, S. Murchie (2013), Hydrous minerals on Mars as seen by the CRISM and OMEGA imaging spectrometers: Updated global view, *J. Geophys. Res. Planets* **118**(4), 831-858, doi: 10.1029/2012JE004145.

Clancy, R.T., M Wolff, M. Smith, B. Cantor, F. Lefèvre (2014), MARCI Global Daily Ozone Mapping and Comparison to LMD GCM Simulations: Polar Dynamics, Hellas Basin, and Heterogeous Chemistry, *5th International Wksph. Mars Atmos.: Modelling and Observation*, Oxford, UK.

Craddock, R. A., A. D. Howard (2002), The case for rainfall on a warm, wet early Mars. *J. Geophys. Res.* **107**, 5111, doi:10.1029/2001JE001505.

Dickson, J.L., J.W. Head, J.S. Levy, D.R. Marchant, D.R. (2013), Don Juan Pond, Antarctica: Near-surface CaCl2-brine feeding Earth's most saline lake and implications for Mars, *Nature Scientific Reports* **3**, 1166, doi:10.1038/srep01166.

Diniega, S., S. Byrne, N.T. Bridges, C.M. Dundas, A.S. McEwen (2010), Seasonality of present-day Martian dune-gully activity, *Geology* **38**, 1047-1050, doi:10.1130/G31287.1.

Diniega, S., et al. (2013), A new dry hypothesis for the formation of martian linear gullies, *Icarus* **225**, 526-537, doi:10.1016/j.icarus.2013.04.006.

Dundas, C.M., S. Diniega, C.J. Hansen, S. Byrne, A.S. McEwen (2012), Seasonal activity and morphological changes in martian gullies, *Icarus* **220**, 124-143, doi:10.1016/j.icarus.2012.04.005.

Dundas, C.M., S. Diniega, A.S. McEwen (2015), Long-term monitoring of martian gully formation and evolution with MRO/HiRISE, *Icarus* **251**, 244-263, doi:10.1016/j.icarus.2014.05.013.

Ehlmann, B.L., M. Dundar (2015), Are Noachian/Hesperian acidic waters key to generating Mars' regional-scale aluminum phyllosilicates? The importance of jarosite co-occurrences with Al-phyllosilicate units, *46th LPSC*, Ab. 1635.

Ehlmann, B.L, C.S. Edwards (2014), Mineralogy of the Martian Surface, A*nn. Rev. Earth Plan. Sci.* **42**, 291-315, doi:10.1146/annurev-earth-060313-055024.

Ehlmann, B.L., J.F. Mustard, S.L. Murchie (2010), Geologic setting of serpentine deposits on Mars, *Geophys. Res. Lett.* **37**, L06201, doi:10.1029/2010GL042596.

Ehlmann, B.L., et al. (2011), Subsurface water and clay mineral formation during the early history of Mars, *Nature* **479**, 53–60, doi:10.1038/nature10582.

Ehlmann, B., D. Beaty, M. Meyer (2014), Developing an updated, integrated understanding of Mars. *Eos, Trans. American Geophysical Union* **95**, 354.

Feldman, W.C., et al. (2002), Global Distribution of Neutrons from Mars: Results from Mars Odyssey, *Science* **297**(5578), 75-78, doi:10.1126/science.1073541.

Forget, F., R.M. Haberle, F. Montmessin, B. Levrard, J.W. Head (2006), Formation of Glaciers on Mars by Atmospheric Precipitation at High Obliquity, *Science* **311**(5759), 368-371, doi:10.1126/science.1120335.

Forget, F., et al. (2013), 3D modelling of the early martian climate under a denser CO_2 atmosphere: Temperatures and CO_2 ice clouds, *Icarus* **222**(1), 81-99, doi:10.1016/j.icarus.2012.10.019.

Grimm, R.E., K.P. Harrison, D.E. Stillman (2014) Water budgets of Martian Recurring Slope Lineae, *Icarus* **233**, 316-327, doi:10.1016/j.icarus.2013.11.013.

Hansen, C. J., et al. (2011), Seasonal erosion and restoration of Mars' northern polar dunes, *Science* **331**, 575-578, doi:10.1126/science.1197636.

Hansen, C. J., et al. (2013), Observations of the northern seasonal polar cap on Mars: I. Spring sublimation activity and processes, *Icarus* **225**, 881-897, doi:10.1016/j.icarus.2012.09.024.

Hansen, C. J,. et al. (2015), Agents of change on Mars' northern dunes: CO_2 ice and wind, *Icarus* **251**, 264-274, doi:10.1016/j.icarus.2014.11.015.

Harmon, J.K., M.A. Slade, R.A. Vélez, A. Crespo, M.J. Dryer, J.M. Johnson (1994), Radar Mapping of Mercury's polar anomalies, *Nature* **369**, 213-215.

Head, J.W., J.F. Mustard, M.A. Kreslavsky, R.E. Milliken, D.R. Marchant (2003), Recent ice ages on Mars, *Nature* **426**, 797-802.

Head, J.W., et al. (2005), Tropical to mid-latitude snow and ice accumulation, flow and glaciation on Mars, *Nature* **434**, 346-351, doi:10.1038/nature03359.

Head, J.W., D.R. Marchant, M.C. Agnew, C.I. Fassett, M.A. Kreslavsky (2006), Extensive valley glacier deposits in the northern mid-latitudes of Mars: Evidence for Late Amazonian obliquity-driven climate change, E*arth Planet. Sci. Lett.* **241**, 663-671, doi:10.1016/j.epsl.2005.11.016.

Heavens, N.G., et al. (2011), Structure and dynamics of the martian lower and middle atmosphere as observed by the Mars Climate Sounder: 2. Implications of the thermal structure and aerosol distributions for the mean meridional circulation, *J. Geophys. Res*. **116**, E01010, doi:10.1029/2010JE003713.

Holt, J.W., et al. (2008), Radar sounding evidence for buried glaciers in the southern mid-latitudes of Mars, *Science* **322**(5905), 1235-1238, doi:10.1126/science.1164246.

Holt, J.W., et al. (2010), The construction of Chasma Boreale on Mars, *Nature 465*, 446-419, doi:10.1038/nature09050.

HSO-SAG (2015), *Candidate Scientific Objectives for the Human Exploration of Mars, and Implications for the Identification of Martian Exploration Zones: Report by the Scientific Objectives for the Human Exploration of Mars Science Analysis Group (MEPAG HSO-SAG), Chaired by* D. Beaty and P. Niles, posted July 2015 by the Mars Exploration Program Analysis Group (MEPAG) at http://mepag.nasa.gov/reports.cfm.

ICE-WG (2015), *ISRU & Civil Engineering Needs for Future Human Mars Missions. Report by the ISRU and Civil Engineering Working Group (ICE-WG), Chaired by* S. Hoffman and R. Mueller, posted December 2015 by the Mars Exploration Program Analysis Group (MEPAG) at http://mepag.nasa.gov/reports.cfm. (Originally presented at the First Landing Site/Exploration Zone Workshop for Human Missions to the Surface of Mars, Houston, TX: http://www.hou.usra.edu/meetings/explorationzone2015/, Opening Plenary video, 1:19-1:48.)

Kieffer, H.H., P.R. Christensen, T.N. Titus (2006), CO_2 jets formed by sublimation beneath translucent slab ice in Mars' seasonal south polar ice cap, *Nature* **442**,793-796, doi:10.1038/nature04945.

Kite, E.S., I. Halevy, M.A. Kahre, M.J. Wolff, M. Manga (2013), Seasonal melting and the formation of sedimentary rocks on Mars, with predictions for the Gale Crater mound, *Icarus* **223**,181-210.

Leshin, L.A. et al. (2013), Volatile, isotope, and organic analysis of martian fines with the Mars Curiosity Rover, *Science* **341**(6153), 1238937, doi:10.1126/science.1238937.

Lee, C., et al. (2009), Thermal tides in the Martian middle atmosphere as seen by Mars Climate Sounder, *J. Geophys. Res*. **114**, E03005, doi:101029/2008JE003285.

McEwen, A.S., et al. (2011), Seasonal flows on warm Martian slopes, *Science* **333**, 740-743, doi:10.1126/science.1204816.

McEwen, A., et al. (2014), Recurring slope linear in equatorial regions of Mars, *Nature Geosciences* **7**, 53-58, doi:10.1038/NGEO2014.

McSween, H.Y., T.C. Labotka, C.E. Viviano-Beck (2015) Metamorphism in the Martian crust, *Meteoritics Planet. Sci.* **50**, 590-603, doi:10.1111/maps.12330.

Medvedev, A.S., T. Kuroda, P. Hartough (2011), Influence of dust on the dynamics of the Martian atmosphere above the first scale height, *Aeolian Res*. **3**, 145-156, 10.1016/j.aeolia.2011.05.001.

Mellon, M.T., R.L. Fergason, N.E. Putzig (2008), The Thermal Inertia of the Surface of Mars, In ***The Martian Surface: Composition, Mineralogy, and Physical Properties***, Cambridge Planetary Science edited by J. F. Bell III, p. 399–427, Cambridge Univ. Press, Cambridge, UK.

Mellon, M. T., et al., (2009), Ground ice at the Phoenix landing site: Stability state and origin, *J. Geophys. Res.* **114**, E00E07, doi:10.1029/2009JE003417.

MEPAG (2015), *Mars Scientific Goals, Objectives, Investigations, and Priorities: 2015,* V. Hamilton, ed., 74 p. white paper posted June, 2015 by the Mars Exploration Program Analysis Group (MEPAG) at http://mepag.nasa.gov/reports.cfm.

Milliken, R.E., J.F. Mustard (2007a), Estimating the water content of hydrated minerals using reflectance spectroscopy. I. Effects of darkening agents and low-albedo materials, *Icarus*, 189, 550-573, doi:10.1016/j.icarus.2007.02.017.

Milliken, R.E., J.F. Mustard (2007b) Estimating the water content of hydrated minerals using reflectance spectroscopy. II. Effects of particle size, *Icarus* **189**, 574-588, doi:10.1016/j.icarus.2006.12.028.

Mitrofanov et al. (2002), Maps of Subsurface Hydrogen from the High Energy Neutron Detector, Mars Odyssey, *Science* **297**(5578), 78-81, doi:10.1126/science.1073616.

Murchie, S.L., et al. (2009), A synthesis of Martian aqueous mineralogy after one Mars year of observations from the Mars Reconnaissance Orbiter, *J. Geophys. Res.* **114**, E00D06, doi:10.1029/2009JE003342.

Murchie, S.L., D.T. Britt, C.M. Pieters (2014), The value of Phobos sample return, *Planet. Space Sci.* **102**, 176-182, doi:10.1016/j.pss.2014.04.014.

Murchie, S., P. Thomas, A. Rivkin, N. Chabot (2015), Phobos and Deimos, In **Asteroids IV**, ed. by P. Michel, in press.

Nair, H., M. Allen, A. D. Anbar, Y. L. Yung and R. T. Clancy (1994) A photochemical model of the Martian atmosphere. *Icarus* **111**, 124-150.

Newman, C.E., M.I. Richardson (2015), The impact of surface dust source exhaustion on the martian dust cycle, dust storms and interannual variability, as simulated by the MarsWRF General Circulation Model, *Icarus* **257**, 47-87, doi:10.1016/j.icarus.2015.03.030.

Nowicki, S.A., P.R. Christensen (2007), Rock abundance on Mars from the Thermal Emission Spectrometer, *J. Geophys. Res. Planets* **112**, E05007, DOI: 10.1029/2006JE002798

NRC (2011), *Vision and Voyages for Planetary Science in the Decade 2013-2022*, Steering Group Chair: Squyres, National Academies Press, Washington DC, ISBN: 0-309-20955-2.

Ojha, L., J.J. Wray, S.L. Murchie, A.S. McEwen, M.J. Wolff, S. Karunatillake (2013), Spectral constraints on the formation mechanism of recurring slope lineae, *Geophys. Res. Lett.* **40**, 5621-5626, doi:10.1002/2013GL057893.

Ojha, L., et al. (2014), HiRISE observations of Recurring Slope Lineae (RSL) during southern summer on Mars, *Icarus* **231**, 365-376, doi:10.1016/j.icarus.2013.12.021.

Ojha, L., et al. (2015), Spectral evidence for hydrated salts in seasonal brine flows on Mars, *Nature Geoscience* **8**, 829-832, doi:10.1038/ngeo2546.

Osterloo, M.M., F.S. Anderson, V.E. Hamilton, B.M. Hynek (2010), Geologic context of proposed chloride bearing materials on Mars, *J. Geophys. Res.* **115**, E10012, doi:10.1029/2010JE003613.

Phillips, R. J., et al. (2011), Massive CO_2 ice deposits sequestered in the south polar layered deposits of Mars, *Science* **332**, 838-841, doi:10.1126/science.1203091.

Pieters, C.M., S. Murchie, N. Thomas, D. Britt (2014) Composition of surface materials on the moons of Mars, *Planet. Space Sci.* **102**, 144-151, doi:10.1016/j.pss.2014.02.008.

Plaut, J. J., et al. (2009a), Radar evidence for ice in lobate debris aprons in the mid-northern latitudes of Mars, *Geo. Phys. Res. Lett.* **36**, L02203, doi:10.1029/2008GL036379.

Plaut, J. J., et al. (2009b), A widespread radar-transparent layer detected by SHARAD in Arcadia Planitia, Mars. *40th LPSC*, Ab. 2312.

P-SAG (2012), *Analysis of Strategic Knowledge Gaps Associated with Potential Human Missions to the Martian System: Final report of the Precursor Strategy Analysis Group (P-SAG)*, D.W. Beaty and M.H. Carr (co-chairs) + 25 co-authors, sponsored by MEPAG/SBAG, 72 pp., posted July 2012 by the Mars Exploration Program Analysis Group (MEPAG) at http://mepag.nasa.gov/reports.cfm.

Putzig, N.E., M.T. Mellon (2007), Apparent thermal inertia and the surface heterogeneity of Mars, *Icarus* **191**(1), 68-94, doi:10.1016/j.icarus.2007.05.013.

Putzig, N.E., M.T. Mellon, K.A. Kretke, R.E. Arvidson (2005), Global thermal inertia and surface properties of Mars from the MGS mapping mission, *Icarus* **173**(2), 325-341, doi:10.1016/j.icarus.2004.08.017.

Putzig, N.E., et al. (2009), Subsurface structure of Planum Boreum from Mars Reconnaissance Orbiter Shallow Radar soundings, *Icarus* **204**(2), 443-457, doi:10.1016/j.icarus.2009.07.034.

Putzig, N.E., et al. (2014), SHARAD soundings and surface roughness at past, present, and proposed landing sites on Mars: Reflections at Phoenix may be attributable to deep ground ice, *J. Geophys. Res.* **119**, 1936-1949, doi:10.1002/2014JE004646.

Putzig, N.E., et al. (2015), Low radar reflectivity in Planum Australe points to past episodes of Martian atmosphere collapse, *46th LPSC*, Ab. 2586.

Rummel, J.D., D.W. Beaty, et al. (2014), A New Analysis of Mars "Special Regions": Findings of the Second MEPAG Special Regions Science Analysis Group (SR-SAG2), *Astrobiology* **14**(11), 887-968, doi:10.1089/ast.2014.1227. (Also posted November 2014 by the Mars Exploration Program Analysis Group (MEPAG) at http://mepag.nasa.gov/reports.cfm.)

Russell, P.R., et al. (2008), Seasonally active frost-dust avalanches on a north polar scarp of Mars captured by HiRISE, *Geophys. Res. Lett.* **35**(23), L23204, doi:10.1029/2008GL035790.

Skok et al. (2010), Spectrally distinct ejecta in Syrtis Major, Mars: Evidence for environmental change at the Hesperian-Amazonian boundary, *J. Geophys. Res. Planets* **115**(E2), E00D14, doi:10.1029/2009JE003338

Smith, I.B., N.E. Putzig, R.J. Phillips, J.W. Holt (submitted), A Record of Martian Ice Ages, *Science*.

Smith, M.D. (2008), Spacecraft observations of the Martian atmosphere. *Annual Rev. Earth* *and Planetary Sci*. **36**, 191-219, doi:10.1146/annurev.earth.36.031207.124335.

Smith, P., et al. (2009), H_2O at the Phoenix landing site, *Science* **325**(5936), 58-61, doi:10.1126/science.1172339.

Thomas, P.C. W.M. Calvin, P. Gierasch, R. Haberle, P.B. James, S. Sholes (2013), Time scales of erosion and deposition recorded in the residual south polar cap of Mars, *Icarus* **225**, 923-932, doi:10.1016/j.icarus.2012.08.038.

Verba, C.A., P.E. Geissler, T.N. Titus, D. Waller (2010), Observations from the High Resolution Imaging Science Experiment (HiRISE): Martian dust devils in Gusev and Russell craters, *J. Geophys. Res.* **115**(E9), E09002, doi:10.1029/2009JE003498.

Watters, T.R., et al. (2007), Radar Sounding of the Medusae Fossae Formation Mars: Equatorial Ice or Dry, Low-Density Deposits?, *Science* **318**(5853), 1125-1128, doi:10.1126/science.1148112.

Wolff, M.J., R. T. Clancy, B. Cantor and R. M. Haberle (2014), The MARCI Water Ice Cloud Optical Depth (Public) Database, *5th International Wksph. Mars Atmos.: Modelling and Observation*, Oxford, UK.

Wordsworth, R.D., et al. (2013), Global modelling of the early martian climate under a denser CO_2 atmosphere: Water cycle and ice evolution, *Icarus* **222**, 1-19, doi:10.1016/j.icarus.2012.09.036.

Wordsworth, R.D., L. Kerber, R.T. Pierrehumbert, F. Forget, J.W. Head (2015), Comparison of "warm and wet" and "cold and icy" scenarios for early Mars in a 3-D climate model, *J. Geophys. Res. Planets* **120**(6), 1201-1219, doi:10.1002/2015JE004787.Wray et al. (2011), Columbus crater and other possible groundwater-fed paleolakes of Terra Sirenum, Mars." *J. Geophys. Res.* **116**, E01001, DOI: 10.1029/2010JE003694.

Wray, J. J., et al. (2011), Columbus crater and other possible groundwater-fed paleolakes of Terra Sirenum, Mars." *J. Geophys. Res.* **116**, E01001, DOI: 10.1029/2010JE003694.

Zurek, R.W., L.J. Martin (1993), Interannual variability of planet-encircling dust storms on Mars, *J. Geophys. Res*. **98**, 3247-3259.

Zurek, R.W., J.R. Barnes, R.M. Haberle, J.B. Pollack, J.E. Tillman, C.B. Leovy (1992), Dynamics of the atmosphere of Mars. In **Mars**, ed. H. Kieffer et al., U. Ariz. Press, Tucson, 835-933.

Zurek, R.W., et al. (2011), Assessment of a 2016 mission concept: The search for trace gases in the atmosphere of Mars. *Planet. Space Sci.*, **59**, 284-291, doi:10.1016/j.pss.2010.07.007.