MEPAG

Report from the 2013 Mars Science Orbiter (MSO) Second Science Analysis Group

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Charter
Mars Science Orbiter Science Analysis Group-2 (MSO-SAG-2)

Introduction

In 2006, the Mars Exploration Program asked MEPAG to prepare an analysis of a Mars science orbiter that could be launched in 2013. This analysis was carried out by means of a Science Analysis Group (MSO SAG-1). SAG-1 started with the following assumptions:

- Assume that the mission has an orbital element, and that for telecommunications purposes, a lifetime requirement of at least 10 years will be imposed.
- Assume the mission is constrained to a total budget no larger than the escalated equivalent of the budget of MRO. (Notwithstanding this assumption, the SAG may consider mission concepts whose scope extends beyond an MRO class mission, particularly if they result in a lot more science for only a little more money.)

The SAG-1 concluded that a very attractive mission could be configured with aeronomy and trace gas measurements (Farmer et al., 2006), and a baseline configuration was proposed.

On Jan. 8, 2007, NASA announced that it had narrowed its selection for the 2011 Scout mission to two possibilities, MAVEN and TGE, both of which are primarily aeronomy missions (and also with some other measurements). Therefore, aeronomy science is no longer appropriate as a focus for the 2013 Mars Science Orbiter. Hence, the Mars Exploration Program requests a new analysis of the science options for MSO, hereby termed MSO-2.

Science Scope for this Analysis

As the Mars Exploration Program is a science-driven and discovery responsive program, the SAG-2 should consider addressing more recent findings from Mars missions such as those related to contemporary gulley formation and cratering rates. For the revised analysis, SAG-2 will use the same telecommunications and financial assumptions as the original SAG-1 (listed above). Although the scientific scope is not restricted, an analysis of the following options is specifically requested:

- Orbital camera(s). Science that can be carried out using one or more cameras that would also be available to support evaluation of landing site safety for future landed missions.
- Atmospheric trace gas. The spatial variation in trace gases in the Martian atmosphere, including methane. This was studied by the SAG-1 and their analysis should prove useful in considering different mission concepts.
- Orbital geophysics. Any class of orbital geophysics that can be mapped to high-priority MEPAG objectives may be considered.
- Landed geophysical package. The Mars Advance Planning Group (MAPG) in its 2006 Update Report identified the option of including a single geophysical lander on MSO. "A case can be made that a geophysical pathfinder would generate some valuable science (although not nearly as valuable as a 4-node geophysical network) (MAPG, 2006; p. 10). The SAG-2 should consider the possibility of one or more landed elements to be launched in 2013, and also the potential to achieve meaningful network science through additional landed elements to be launched at later opportunities,

Requested Tasks

1. Determine the primary combinations of the above classes of science investigations that fit within the overall assumed cost and engineering constraints, and that constitute possible mission concepts.
    a. Estimate the orbital parameters for the different mission concepts.
    b. Analyze the trades between the science and telecommunications objectives (e.g. orbits, phasing) for each mission concept
2. Analyze the degree of alignment of the different mission concepts with the NRC's Decadal Survey and with MEPAG's priority system and the MEPAG Goals document.
3. It is not necessary to develop a comparative prioritization of the multiple mission concepts. The SAG-2 analysis work will constitute input to a HQ-chartered Science Definition Team, who will evaluate the relative priorities.
4. Human precursor measurements. Consider the implications of the different mission concepts for the eventual human exploration of Mars, and identify the potential opportunities for contributions from other NASA Directorates. Presumably, measurements made to support the preparation for human exploration can also be applied to scientific objectives.
5. Engineering support for future missions. In addition to telecom relay capability, consider whether there are other engineering-related measurements that would be of value to the Mars Exploration Program's future mission. For example, how important is a system that can monitor the upper atmospheric density to allow aerobraking or aerocapture of missions in the second half of the decade?

Methods

- SAG-2 will conduct their business primarily via telecons, e-mail, and/or web-based processes. One to two face-to-face meetings may be accommodated if needed.
- If added expertise is needed, SAG-2 can consider requesting a briefing or possibly adding the person to the SAG.
- The SAG will be supported by a small group of JPL mission engineers in their consideration of potential costs.
- Logistical support will be provided by the Mars Science Office at JPL.

Timing

- The SAG will begin its discussions as soon as possible. A draft report will be reviewed by the MEPAG Executive Committee and by MEP is requested by April 15, 2007.
- A midterm status check by Michael Meyer, David Beaty, and Ray Arvidson is requested by about March 1, 2007.
- A final report is requested by May 15, 2007.

Report Format

- The SAG-2 report of findings will be presented in the form of both a PowerPoint presentation and a text white paper. Additional supporting documents may need to be prepared. After the report has been accepted by program management (including MEPAG Executive Committee), it will be posted on a publicly accessible website.
- The report will not contain any material that is ITAR-sensitive.

References

Farmer, B., et al., 2006, Mars Science Orbiter (MSO): Report of the Science Analysis Group, Unpublished white paper, 48 p, posted April 2006 by the Mars Exploration Program Analysis Group (MEPAG) at http://mepag.jpl.nasa.gov/reports/index.html.

Mars Advance Planning Group (2006), 2006 Update to "Robotic Mars Exploration Strategy 2007-2016," Unpublished white paper, 24 p, posted Nov. 2006 by the Mars Exploration Program Analysis Group (MEPAG) at http://mepag.jpl.nasa.gov/reports/index.html.

Michael Meyer, NASA Senior Scientist for Mars Exploration, NASA HQ
David Beaty, Mars Program Chief Scientist, JPL
Ray Arvidson, MEPAG Chair

January 18, 2007

Executive Summary

A scientifically bold orbital mission in 2013 can address profound and basic scientific gaps that remain in the era beyond MRO. Not surprisingly, there is no single instrument complement that addresses all of the highest priority science, and the science analysis group identified three primary mission scenarios that would address multiple objectives. The high priority measurements are each traceable to MEPAG and NRC goals. These measurements are directly linked to the requested science study areas of the Charter and other areas where critical gaps in current knowledge exist.

All three scenarios address a theme of "Dynamic Mars: Activity, Transport and Change". Any one of these three scenarios will return significant new information relevant to our understanding of the planet, its history and its potential for life.

- ***Plan A: Atmospheric Signatures and Near-Surface Change:*** This plan addresses the charter task to examine relatively short-lived atmospheric trace gases and follows up on discoveries of recent surface activity, such as new gullies. The intention is to provide a comprehensive characterization of the chemical composition of the Martian atmosphere, its global distribution and variation with season, with particular sensitivity for the ultra-low abundance species that might be signatures of subsurface processes related to existing habitable zones and possible life. The record of global climate measurements of atmospheric temperature, dust, water vapor, and surface albedo would be continued while providing new measurements, such as direct measurements of wind, that uniquely constrain and validate models of atmospheric dynamics and transport.

- ***Plan P: Polar and Climate Processes:*** This plan approaches the orbital imaging and geophysics elements of the charter through the lens of the dynamics of volatile reservoirs and modern climate. This scenario follows up on discoveries of active erosion of the residual south CO_2 ice cap and anticipated new results from the 2008 Phoenix polar lander. The focus is a detailed examination of the mass/energy balance through monitoring of both poles in space and time. Precise elevation and volume of seasonal and residual volatile deposits will allow a time variable measure of mass in exchange with the atmosphere and estimates of exchange with lower latitude volatile reservoirs at different epochs. The record of global climate measurements, particularly albedo and temperature relevant to energy balance, will be continued and new direct measurement of winds will improve models of surface-atmosphere interactions at all latitudes.

- ***Plan G: Geological and Geophysical Exploration:*** This plan satisfies specific Charter requests to examine high-resolution imaging, orbital geophysics, and a landed geophysical package. The plan would follow up on discoveries such as the present-day (last decade) impact events and debris flows associated with gully activity. The first exploration of the uppermost few meters of regolith and mantling materials, and topographic change detection over broad regions is provided. The landed package would address high priority interior objectives such as seismic activity and structure of the crust, mantle and core, in addition to surface measurements of temperature, water vapor and dust electrification in the planetary boundary layer.

The SAG did not prioritize amongst the three scenarios, in that:

- No single scenario can complete the remaining significant orbital science to be accomplished in the wake of MRO.
- Each scenario addresses key (but different) MEPAG goals.
- All scenarios feed-forward to missions currently under study for 2016, 2018 and 2020 (e.g., Network, Sample Return, Astrobiology Field Lab, Mid-range Rovers) and to support of planning for human exploration, although each scenario has stronger ties to some missions than others.

Variations of these three thematic scenarios were then grouped into three tiers of mission science, based on completeness, synergy, and ROM costs:

- ***Core Mission Concept (CMC):*** This level provides the best combination of investigations focusing on one of the above science scenarios while keeping key cross-disciplinary elements and staying within reasonably constrained resources of mass and cost.
- ***Augmented:*** These scenarios added another complementary science thrust to the CMC. These options were in line with the MRO-class flight system capabilities but would require significantly increased funding and/or contributed elements to achieve the expanded suite of science objectives.
- ***Reduced:*** This level is consistent with the nominal cost target provided by the project. However, the SAG judged these options to be much less desirable as they required significant compromises with regard to measurement goals or supported too few cross-disciplinary elements.

Findings:

- The SAG strongly preferred the Core Mission Concepts over the "reduced" options, since the gain in science for the modest augmentation was very high and preserved the cutting-edge cross-disciplinary elements that are the hallmark of a core mission.
    - To this end, no single component should dominate the payload, and a landed element should not preclude significant, innovative orbiter science.
- A single lander emphasizing geophysical measurements (including meteorology) is scientifically credible and could be paradigm-shifting. However, the notional lander system presented to the SAG appears to be inadequate in cost and mass.
- The implementation required by each scenario is sufficiently different (e.g., orbital inclination or possible inclusion of a landed component) that it will require an early selection amongst the three scenarios.
- International contributions could help with cost, but they (or their requirements) need to be carefully reviewed to ensure that key measurements will be met.

Programmatic Decisions Required Prior to the Science Definition Team (SDT)

- Is the drop-package to be a key component of the MSO mission?
- On which scenario should the SDT focus?
- What cost and mass resources will be baselined for MSO?

1 Background

In the winter of 2005/2006, a Science Analysis Group (SAG-1), chaired by C. B. Farmer was convened to examine the 2011/2013 launch opportunity. That group deliberated via telecon and email and delivered a final report in March of 2006 that analyzed science goals focused on the atmospheric evolution of Mars through study of the exosphere and atmospheric escape, and the composition and circulation of the lower atmosphere (available via the MEPAG web site http://mepag.jpl.nasa.gov/reports/MSO_SAG_report_071006.pdf). The primary measurements emphasized characterization of loss of water to space through the upper Mars atmosphere, complemented by measurements of key biogeochemical gases (particularly methane) in the lower Mars atmosphere, possibly identifying local areas for future landed exploration. The cost of mission, with straw-man payload, was included in 2006 POP guidelines and was carried over to 2007.

In January of 2007, two Mars Scout investigation teams, both focusing on the upper atmosphere processes and escape to space, were selected for a head-to-head competition for the 2011 launch opportunity. A new Science Analysis Group (SAG-2) was formed to re-evaluate scientific options for the 2013 launch opportunity. The Charter for the SAG-2 is provided as a preface to this document.

2 Deliberations/Process

Calvin agreed to Chair the SAG-2 in the latter part of January 2007. In consultation with the executive committee, Michael Meyer, Dave Beaty and Ray Arvidson, committee members were selected to address the specific scientific analysis requested in the Charter as well as span the breadth and diversity of Mars science under consideration. The group was under a rapid timeline to deliver a final report in 3.5 months in order to expedite the process through Science Definition Team (SDT) and Announcement of Opportunity (AO) with a desired release date in early 2008. The group met weekly by teleconference from Feb 7 to May 16, 2007 and 8 members of the SAG-2 met for a face-to-face meeting at the annual Lunar and Planetary Science Conference in March.

On average, each weekly telecon was attended by 13 of the 16 SAG members though participation in any given week varied. In March and April several additional Friday or Monday phone meetings were scheduled but with lighter attendance. Calvin distributed comprehensive written notes after each meeting so that those unable to attend would be up to speed with the conversation. In addition, a lively and extensive email exchange occurred, with between 15 and 50 emails traded each week on a variety of topics.

The initial meeting allowed the SAG-2 to discuss the Charter and basic mission constraints with the Executive committee and the Mars Science Orbiter (MSO) project office, represented by Tom Komarek and Daniel Winterhalter as the Study Scientist and liaison to the project.
Early conversations outlined properties that should be representative of a program core mission (Section 3) as well as discussed overarching themes (Section 4) that are relevant given the wealth of new information and discovery in the past decade of Mars exploration. A comprehensive list of forward-thinking science goals was developed by the entire SAG-2

(Section 5). These goals incorporated the specific science analysis requests in the Charter. Given the emphasis on volatiles in the recent NRC decadal survey, an additional major set of goals in the area of polar processes emerged. In order to focus the dialog on the next critical measurements the SAG-2 was split into four sub-groups along discipline lines, where the key measurements were further refined (Section 6). High priority measurements were defined and strawman payload instruments were identified that can accomplish the measurement goals (Section 7). Numerous potential combinations of instruments were considered and the SAG-2 ultimately reduced these to three scenarios with science synergies, diverse feed-forward ability and within the evolving cost guidelines that were provided to the SAG-2. These scenarios are described in Section 8. The MSO project looked at one of these scenarios in light of mission implementation (Section 9), though specific mission trades will need to be explored in more detail by the SDT. In Section 10 we consider how these scenarios will support future (including human) exploration. Specific science issues that were discussed, some of which were resolved, and others not, is given in Section 11. We conclude (Section 12) that there is ample innovative science to be done in orbit at Mars.

3 Core MSO Mission Attributes

An outcome of early discussions was to classify properties that distinguish a core Mars Exploration Program (MEP) mission from competed Scouts and smaller focused objectives. The SAG-2 agreed to the following guidelines to help define mission scenarios and combinations of science goals.

1) Ability to address multiple science objectives with a wide range of potential instruments. Measurements/Instruments are linked either through a broad theme or through synergy available among observations.
2) Strawman payload should not be over-specified, but provides feasibility and allows creative solutions to achieve the desired science objectives to arise from the community.
3) Provides the opportunity to do science that is "too big" for Discovery or Scouts.
4) Either makes a new measurement, not previously done at Mars, or augments existing measurements such that the data can provide a paradigm shift or significant advance in our understanding of the planet.
5) Makes a significant step or definable progress against programmatic goals by either building on past discoveries or enabling future strategic missions.

4 Themes

The group considered a number of overarching scientific themes that might serve to steer the Mars Exploration Program in the decade following the ongoing and highly successful "Follow the Water" campaign. It is clear that this goal has indeed resulted in multiple locations where water has been shown to have interacted extensively with the rock record and identified high priority candidates for future landed missions. Among the broad themes discussed were those of habitability or habitable zones, dynamics or contemporary processes including atmospheric, polar and geologic processes, ancient environments, and evolution of a livable planet. In addition to these themes, a list of more specific topics was generated with regard to specific science or measurement objectives. These topics are outlined in the next section.

5 Science Scenarios

A number of high priority observations are identified in various MEPAG and NRC documents. Most recently, the Mars Advanced Planning Group (MAPG) published a detailed report on the strategy for robotic exploration of Mars followed by an update in response to review by the NRC (MAPG 2006). Additional detailed goals are outlined in the MEPAG "Goals" document (http://mepag.jpl.nasa.gov/reports/MEPAG%20Goals_2-10-2006.pdf), and numerous reports from COMPLEX and the Space Studies Board. The SAG-2 operated under the ground rules that the Mars Reconnaissance Orbiter (MRO) would achieve its minimum mission success criteria and we would be focusing on new science that would meet well-established priorities from these and earlier reports. Due to the competition sensitive nature of the 2011 Scout missions the SAG-2 was not provided with any additional information other than what was in the press release regarding the selection for Phase A studies. Our assumption was that neither MAVEN nor TGE would fully address either the measurement goals associated with trace gasses or lower atmosphere circulation and these remained as important components of our science deliberations. Discussions first focused on defining new science requirements before getting into the details of the mission technical implementation.

A period of "idea generation" via phone and email generated a fairly expansive list of science topics that would be fruitful in the post-MRO decade and these were further winnowed into science scenarios that were felt to be the most immediately compelling. A brief outline is provided here. In Section 6 a detailed description of specific observations, measurement goals and justification for each objective is provided.

1) Atmosphere and Climate: The high priority goals identified both in MAPG 2006 and in the SAG-1 report include following the MSL mission with the ability to globally map and locate potential sources of methane and other trace gasses, as well as detailed observation of the near-surface meteorology and atmospheric boundary layer conditions.

- a) Atmospheric Composition (Signatures) and Transport
  - i) Trace gas constituents
  - ii) Sources
  - iii) Dynamics (Transport)
- b) Climatological Monitoring and Atmospheric Processes
  - i) Modern Climate and Global weather
  - ii) CO2, Water, Dust cycles (winds)
  - iii) Interannual Variations
  - iv) Regional surface changes (coupled to climate)

2) Polar, Glacial and Periglacial Processes: As outlined in the MAPG 2006 report, a quantitative understanding of surface-atmosphere fluxes and thermal balance will require higher temporal observations than afforded by the short-lived 2008 Phoenix lander. The SAG-2 developed a set of specific objectives to address the broad questions emerging from the polar community, specifically:

- a) Mass and energy budgets and nature and time scales of processes which control these

b) Volatile and dust exchange between polar and non-polar reservoirs and relation to past and present distribution of subsurface ice
c) Physical characteristics and relationship between geologic units
d) Chronology, compositional variability, and record of climate change in the layers
e) Age of the PLD and glacial, fluvial, depositional, erosional, flow history

Although the MAPG report treats both structure and interior of Mars and surface and near-surface processes under the "Geology" theme, the SAG-2 divided this into two working groups, consistent with the charter to explore landed geophysics and orbital geophysics as separate elements.

3) The surface rock record aka "Geology": These areas all link to a general understanding of the surface and shallow subsurface geologic record, and its implications for past/present climate and habitability. The SAG-2 concentrated on the next generation of measurements that target particular issues and can be performed from orbit -- subsurface imaging and improved spatial or spectral coverage by imagers and spectrometers.

a) Ancient Environments
    i) Sedimentary rock depositional setting
    ii) Stratigraphic relationships (sedimentary and igneous)
    iii) Burial and exhumation of landforms and cratered surfaces
b) Contemporary Processes (Dynamic Mars)
    i) Gullies (Fluvial and mass-wasting)
    ii) Polar landform change
    iii) Physical properties of the upper layers of PLD
    iv) Links between hydrogen signature and near-surface features.
    v) Aeolian processes
    vi) Surface deformation or active endogenic processes
    vii) Current impact rate and surface age

4) Inside Mars aka "Geophysics": Network science and interior geophysical measurements have been a recognized priority in Mars Architecture and NRC documents for several decades. In particular a surface network of sensors was recognized as one the "next best steps" for the Geology goal in the MAPG 2006 report and the SAG-2 concentrated on what could be accomplished with a single landed package that would feed-forward to network science at a future date.

a) Size, density and state (solid or liquid) of the core
b) Thickness, density and stratification of the crust
c) Density and layer of the mantle
d) Seismic activity (frequency and distribution)
e) Heat flow and lithosphere thickness (both related to thermal gradient)

6 Science Goals By Group

From the outline in the previous section, discipline sub-groups of the SAG-2 further refined the specific observations and their links to MEPAG, MAPG and NRC documents.

6.1 *Atmospheric Science*

Atmospheric Science for MSO is comprised of two major scientific investigations: (1) Atmospheric Signatures and (2) Atmospheric State. While the Atmospheric Signatures investigation requires knowledge of atmospheric state, the Atmospheric State investigation itself is a uniquely important investigation for the Mars Exploration Program. In the predecessor MSO SAG-1 report, Atmospheric Signatures and Atmospheric State were referred to as Lower Atmosphere Composition and Circulation and were adopted, along with Aeronomy, as the foci of the mission.

6.1.1 Atmospheric Signatures

6.1.1.1 Background

The Atmospheric Signatures investigation is aligned with NASA's search for life beyond Earth, as well as understanding modern sources of activity (volcanic, tectonic) on Mars.

The existence of subsurface habitable domains on Mars is suggested by several observations. Some geomorphic evidence indicates that Mars has been volcanically active in its recent past; there are volcanic craters that may have been formed 1 million years ago. While ongoing extrusive volcanism does not occur today, there is no conclusive evidence that intrusive volcanism does not exist in the present epoch. In the frozen Martian subsurface, geothermal systems resulting from intrusive volcanism would likely be habitable locales. There is evidence for shallow groundwater in the recent past and perhaps today. Indeed the images indicating recent gully activity have been interpreted as being the result of a transient flow of liquid water.

As on Earth, a wet subsurface environment can provide chemical gradients that can power biological activity. The terrestrial experience shows that extremophile life forms inhabit almost any environmental niche where even minimally supportive conditions exist. Therefore, if life ever existed on Mars in the past, life could still be present today if subsurface habitable domains existed throughout the course of Mars history.

Both geological processes and biological activity introduce disequilibrium into the environment, including the production of gases that could be injected into the atmosphere. It has long been suggested that the most effective first approach for detecting the presence of extant geological or biological activity would be to perform a survey of atmospheric composition seeking evidence for disequilibrium chemical constituents. However, it would be important to understand which atmospheric constituents in very low abundance (so-called "trace species") are simply due to the background abiogenic photochemistry acting upon the major atmospheric species and which could not be formed in the atmosphere and must necessarily be introduced by a non-atmospheric process, be it endogenic or exogenic. These chemical compounds of non-atmospheric origin can be signatures ("atmospheric signatures") of active geological and biological processes that are difficult to detect otherwise. Indeed, the search for atmospheric signatures on extraterrestrial planets is the keystone of NASA's Navigator Program objective seeking evidence of life elsewhere in the galaxy.

Several geological processes can result in volatiles being introduced to the atmosphere, including direct degassing from magma rising from the subsurface storage regions through the crust, magma degassing into shallow hydrothermal systems, and interaction of rocks with hydrothermal solutions or ground waters. The molecular composition of released gases likely differs from that on Earth and will depend on several variables, including temperature of equilibration, pressure of degassing, and oxidation state. High temperature promotes CO, and to a lesser extent H_2, whereas at low temperature, H_2S, S_2, and H_2O is preferred. Low temperatures also favor CH_4 and NH_3—in fact, these species are likely to be negligible in volatiles directly released from magmas but could be abundant in volatiles released from hydrothermal systems or via lower temperature water-rock reactions. Although water is present as a low-level background gas, local enhancements in water may provide an additional signature of subsurface geothermal activity.

Terrestrial microorganisms produce a wide variety of gases as products of both energy-yielding oxidation-reduction (redox) reactions and synthesis and decomposition of organic matter. For example, hydrogen-rich compounds including CH_4, NH_3, H_2S, volatile hydrocarbons, and alkylated amines and sulfides will form during fermentation and anaerobic respiration under strongly reducing conditions. Nitrogen redox reactions produce nitrogen oxides (NO and NO_2), and N_2O. The thermal decomposition of biogenic sedimentary organic matter produces light hydrocarbons. Terrestrial volcanic hydrothermal systems provide abundant sources of chemical energy that sustain the most robust and diverse subsurface microbial populations known. Even in the absence of active volcanism, aqueous alteration (serpentinization) of ultramafic (Fe- and Mg-rich) volcanic rocks or radiolytic decomposition of water can provide H_2 to sustain subsurface life. The oxidation of Fe^{2+}, S and/or C associated with groundwater circulation through other types of rocks also can provide energy for microorganisms.

In the earliest discussion of the detection of life on Mars, Hitchcock & Lovelock suggested that the presence of reduced gases, such as CH_4, in an oxidizing atmosphere was direct evidence of life. Since that time, as previously discussed above, it is now understood that geological processes also introduce disequilibrium into the environment and geothermal activity can inject such gases into the atmosphere. Thus, the recent putative detections of Martian atmospheric CH_4, have stimulated numerous hypotheses about the nature of the methane sources, their magnitude, and locales. Efforts to identify the sources of terrestrial methane have found that measurements of CH_4 isotopologues do not necessarily distinguish between possible abiogenic and biogenic sources. However, it has been found that the abundances of other cogenerated species, such as ethane (C_2H_6), relative to CH_4 can distinguish between a source from active biology and other potential sources; the C_2H_6/CH_4 abundance ratio is $<10^{-3}$ for the former, while other sources produce nearly equivalent amounts of CH_4 and C_2H_6.

The discovery of either extant geothermal or biological processes and their source locations would have profound implications for astrobiology and the Mars Exploration Program (MEP). The case involving active microbiology is clear. Identifying the locations of active geothermal processes also would be profound. Such places would be obvious targets for future surface exploration. If these environments were found to be supportive of life, but nevertheless lifeless, then fundamental astrobiological concepts would be challenged. The reported observations of methane have suggested a seasonal variability in the CH_4 abundance and meridional and longitudinal variability, implying that the distribution of CH_4 could reveal the location of its source. However, current Martian atmospheric photochemical models indicate that its lifetime is ~250 Mars years, which is so much longer than atmospheric transport timescales that the expectation is that CH_4 should be well-mixed throughout the atmosphere. If the reported spatial variability is true, then some atmospheric chemical processes (possibly dust-related) have been seriously underestimated in the current models. On the other hand, if observations with significantly higher precision show that CH_4 is well-mixed, then its distribution will not be a useful guide to locations of active processes. However, many of the cogenerated species have much shorter atmospheric lifetimes and therefore could be tracers leading back to source zones. In addition, atmospheric signatures of non-methanogenic active geological and/or biological processes may directly lead to their source regions.

6.1.1.2 Goals

The overarching goal of the Atmospheric Signatures investigation is to characterize the astrobiological potential of Mars. The specific scientific approach of using atmospheric composition as a tool for this astrobiological exploration may allow detecting subsurface zones of interest that cannot be characterized easily otherwise.

This investigation has four specific objectives:

1) Identify chemical constituents in the atmosphere that cannot be formed by atmospheric photochemical processes starting with CO_2, H_2O, N_2. Besides the tentative CH_4 detections, other chemical signatures arising from possible active subsurface processes may be present in the atmosphere, but specifically which is not known.

2) Locate sources regions of detected atmospheric signatures associated with habitability and habitance. Knowledge of a source region provides direction for later missions. Furthermore, even if the detected atmospheric signatures were only from active abiogenic geological processes and thus leading to the locations of only habitable domains, life that doesn't introduce detectable atmospheric signatures might still exist in these places.

3) Determine atmospheric lifetimes of signature species. Knowledge of lifetimes is necessary for indirectly locating a source region and for characterizing the magnitude of the source process.

4) Determine character of process producing signature species. To the extent possible, distinguish between abiogenic and biogenic origins. It may be feasible to identify the existence of active biological processes without waiting for in situ analysis or sample return.

6.1.1.3 Measurement Priorities

What atmospheric signatures of active processes that might be present and at what abundances is unknown—this is both a challenge and a major exploration opportunity. Therefore, to accomplish the Atmospheric Signatures objectives, the measurement requirement is to sensitively detect a diversity of signature molecules over broad temporal and spatial scales–not only methane.

Molecules diagnostic of active geological and biogenic processes include sulfur, nitrogen, and reduced carbon species. These gases will have very low abundances in the Martian atmosphere. Previous detection attempts have been basically unsuccessful; the 10 ppbv detection of CH_4 is considered to have large uncertainties and the actual abundance may be much less. Much more sensitive methods, robust to false positive detection, are required to properly constrain the flux of biogenic- or geologically-derived gases to the Martian atmosphere.

The detection of an atmospheric constituent in extremely low abundance is made secure only when its presence is confirmed by simultaneous measurement of multiple spectral features. In turn, simultaneous detection of different species can serve as important evidence for the identity of potential source processes; cogenerated species may span several orders of magnitude in abundance. There is generally a trade between detection sensitivity and spatial and temporal resolution. For the purpose of maximum understanding of signatures present in the atmosphere and their seasonal abundance, a detection threshold of at least a few parts per trillion for a zonal average over 5° of latitude is necessary to significantly exceed current observations. To accurately derive the abundance of the signature, simultaneous measurement of temperature also is needed.

It is not known where on Mars habitable zones might exist, and where such zones might harbor active biological processes. As a result, the search for atmospheric signatures must be global and must be performed from orbit. While long-lived species will be widely distributed, many trace signature molecules have short chemical lifetimes and, consequently, will be detectable only near their sources. These sources will generate plumes, the dynamics of which suggest spatial scales of a few tens of kilometers to hundreds of kilometers. However, actual source vents (as on Earth) are likely to occur at scales from 10's of meters to ~ 1 km. The detection of such plumes, therefore, requires sampling of the full Martian surface with individual measurements having a resolution of better than 10^4 km^2 and a sensitivity at least ~1 ppbv, and preferably tens of pptv.

To tie an observed plume of chemicals to its surface source in an optimal fashion, both measurements that resolve the plume structure and knowledge of the wind field are needed. The latter requires knowledge of the atmospheric state—both temperature fields and the distribution of aerosols—on a global scale with a vertical resolution of <1 scale height. Observation of a detectable signature gas with an appropriate lifetime (e.g., SO_2), can be used to identify interesting source regions, particularly in conjunction with transport modeling. Direct observations of wind with current technologies are inadequate to track species back to localized sources, but they provide the validation needed to have confidence in using circulation models to track the signature species back to its source region.

Knowledge of the atmospheric lifetime of a signature species is required to estimate the flux emanating from the surface from observations of an atmospheric plume and to facilitate application of inverse modeling techniques for source location. This requires an understanding of the background atmospheric chemistry, which will be improved by observations of the vertical distribution of composition, temperature, and dust (at 1/2 scale height resolution). In addition, observations are required under all atmospheric conditions, in particular over the range of dust loading, to assess the potential impact of heterogeneous chemistry, including electrification-related processes; the requisite measurements of species and temperature distribution must be unaffected by the degree of atmospheric dust content.

Besides episodic events, both climatic and biological phenomena may introduce a seasonal signal into the atmospheric composition. Low volatility molecular species may be depleted as ice caps form and reappear as they sublime. When the latter occurs, resulting atmospheric concentrations may be particularly elevated. As on Earth, any biosphere may introduce a distinct atmospheric seasonal cycle. Therefore, it is necessary to monitor the atmosphere over a Martian year over a broad latitude range and with observations at every latitude at least once per season to optimize detection of seasonal variability and more frequently to optimize detection of episodic events.

6.1.2 Atmospheric State: Orbital Science

6.1.2.1 Background

Atmospheric state refers to the description of atmospheric thermal structure, pressure, winds, energy balance at the surface (albedo and thermal inertia), the distributions of atmospheric aerosols (dust and ice) and volatiles (water vapor and carbon dioxide), including their partitioning between the atmosphere and surface, all as a function of space and time. Of particular interest are the variation of atmospheric structure and composition on time scales ranging from day-to-day, with season, and from year-to-year. These reveal the processes controlling the present atmospheric circulation and climate and provide insight into climate change, including that driven by cyclic variations in distributed sunlight as affected by orbital and obliquity changes.

In the present thin, dynamically and radiatively active Martian atmosphere, the strongest climatological signals are the seasonal and daily cycles, followed by the interannual variations driven by changes in the volatile reservoirs, such as the residual polar ice caps, and in the redistribution of dust, the latter being most dramatic in the episodic occurrence of great dust storms in some Mars years, but not others. The establishment of a multi-year climatology has been a major success of the modern exploration of Mars, with seasonal coverage of the global distributions of temperature, dust, water vapor, carbon dioxide and surface albedo spanning more than 3 Mars years, principally by the Mars Global Surveyor and now continuing with Mars Express and the Mars Reconnaissance Orbiter. The Mars Science Orbiter (MSO) provides a unique opportunity to extend and to build upon that climatological record.

This climatological record and the processes that it captures have been—and will continue to be—exploited in two ways. First, it provides direct evidence of the key climate processes and provides the data needed to validate our numerical simulations of the Martian climate. Thanks to key physical similarities between Earth and Mars (shallow atmospheres driven by sunlight on a rapidly rotating planet), numerical models developed to understand the Earth's weather and climate have been adaptable to Mars and form a key part of our understanding of how the climate system works. Second, these numerical climate models have provided the means to simulate processes and phenomena, which cannot today be observed directly, at least at the necessary spatial scales and temporal frequencies. In addition to providing scientific insight, these simulations are extensively used in the design and implementation of critical mission phases such as aerobraking, entry-descent-and-landing (EDL), and surface operations. Thus, a major use of atmospheric state data is to validate that the simulations are accurate in describing the observable environment, increasing our confidence that they are representative of the unobserved environment.

6.1.2.2 Goals

The two goals for MSO with regard to the atmospheric state are: 1) Extend the present climatology to characterize interannual variability and long-term trends of the atmospheric state, circulation, and cycles of dust, water, and carbon dioxide; and 2) Provide new observations that constrain and validate models of atmospheric dynamics and state. Both these goals require extended and frequent global coverage over at least one—and preferably multiple—Mars years.

6.1.2.3 Measurement Priorities – 1: Extend the Climatology

Extension of the present climatology requires daily, globally representative measurements of atmospheric phenomena (hazes, clouds, storms, etc.), of surface albedo and compositional changes (dust and ice), and of atmospheric thermal structure over several Mars years. Column measurements of dust opacity and water abundance are essential, and vertical profiles with better than one-scale-height resolution over the appropriate altitude ranges are highly desired (see the Atmospheric State – Orbital Science Table).

6.1.2.4 Measurement Priorities – 2: New observations for model validation

The first critical need is the observation of winds day-to-day over the globe with some vertical resolution. It is unlikely that existing technology can provide the high spatial resolution and precision needed to use winds directly in analyses of energy exchange and transport or in simulations of flight dynamics and of surface operations. However, it should be possible within the MSO resource envelope to make wind measurements (say to a precision of 10 m/s over an atmospheric scale height ~ 10 km) that can adequately test model simulations of atmospheric transport and climate change.

A second critical need is the ability to cleanly describe both the atmospheric heating (and thus suspended dust) that drives the circulation and the atmospheric response (e.g., temperature and water vapor distributions). Past measurements of temperature, dust and water may have been biased by the difficulty of cleanly separating the retrieved quantities using measurements ranging in the ultraviolet to thermal IR part of the spectrum. The requirement is to measure temperature and water vapor independent of dust conditions; a different measurement approach is then needed to characterize the dust itself.

A major benefit of temperature and water vapor observations that are not compromised by the presence of dust is that these fields can be retrieved within the lowest scale height of the atmospheric regardless of the dust loading. Half-scale height vertical resolution can extend the retrievals to within a few kilometers (< 5) of the surface, revealing new features of storms and surface-atmosphere exchange processes.

6.1.2.5 Synergies

With the measurements described above and with the improved transport/climate models that will result from them, it should be possible to better describe surface-atmospheric interactions (dust lifting, storm generation, volatile sublimation/condensation) key to many climate processes. It should also be possible to do the inverse problem of tracing spatially varying minor atmospheric constituents (or trace gases, water being one) to localized source areas. The ability to do this—or alternatively, the uncertainty of the source region size—depends strongly on the nature of the source and the lifetime of the traced gas. Of particular interest would be to capture the trace gas evolution in different seasons and under different (dust) storm conditions. Multi-year coverage increases the probability that a representative suite of dust activity will be captured.

6.1.3 Atmospheric State: Landed Science

6.1.3.1 Background

Detailed meteorological measurements have been obtained from only 3 locations on Mars; the two Viking Landers and Pathfinder (which was very similar meteorologically to Viking I). The MER rovers did not carry a traditional meteorology package and the Phoenix lander has a relatively simple meteorology package. Because of this paucity of observations, there still remain many questions about the processes that occur at the interface between the surface and atmosphere on Mars. There are also important engineering considerations for the safe delivery and operation of spacecraft to the Martian surface that give more incentive to observe the atmosphere from the surface.

6.1.3.2 Goals

The first and most basic question that one would address with a landed meteorology package at Mars would be one of better understanding how representative the previous 3 observation locations are to Mars in general. Just as on Earth, weather is an inherently local phenomenon, so there is always advantage in characterizing its behavior under meteorologically distinct settings. To satisfy this goal, even a relatively basic, but complete meteorology package could suffice.

Martian meteorology is punctuated by dramatic dust storms and dust devils, both of which may have significant consequences for the climate, weather and even perhaps chemical makeup of the atmosphere. For Mars, it is important for the standard meteorological observations to not only characterize the typical conditions, but also those of the extreme events. This is best accomplished by sending capable instrumentation and adapting its observational behavior during these infrequent events to best capture their special properties.

The types of questions that are now of interest at Mars extend beyond these simple meteorological quantities. In particular, the questions more directly address the interaction between surface and atmosphere, in terms of transports of mass, momentum and heat between the two reservoirs. This drives us to more sophisticated observations than the simple, classic meteorology packages that have been sent to Mars. These “next-generation” measurements address the boundary layer on Mars, and the processes that control the mixing of mass, heat and momentum through this layer connecting surface and atmosphere. On Earth, this type of observation is typically done by directly measuring the eddy fluxes through the boundary layer.

This is now becoming feasible for Mars as well, and is required to advance our understanding of Mars.

Another advantage of obtaining these ‘next-generation’ boundary layer measurements from the surface of Mars is that it will allow us to more fully validate the many types of atmospheric models in use for Mars. Because our modeling capabilities have advanced dramatically since even the time of Pathfinder, we are now in a position where the models are significantly underconstrained by the available data. More sophisticated observations are needed that can place more stringent constraints on the models (ranging from simple 1-D models to large eddy simulations, mesoscale models and global circulation models), and should be done to allow maturation of these models and our general understanding of the interaction of Mars surface and atmosphere.

In addition to understanding the fundamental boundary layer processes described above, there is also great desire to better understand the processes controlling the stability of water in all phases as it is transported between surface and atmosphere. On Earth, this is typically done with a “closure experiment”, where the factors forcing the transport and stability of water are measured, as well as the actual distribution and transport of water itself. Again, these observations are now becoming feasible for Mars. This approach, where the processes that control water stability on Mars become better understood, will allow us to extrapolate to other locales on Mars, as well as other epochs to predict the behavior of water at those times and places.

Finally, the possible significance of dust electrochemistry on the lifetime of biosignatures has recently been recognized. While theoretical work on this problem is moving ahead, direct observations of dust electrification effects would place this work on much stronger footing. Instrumentation to measure this is now lightweight and simple, and should be considered part of a nominal meteorological station for Mars.

6.1.3.3 Measurement Priorities

Pressure and temperature constitute the most basic meteorological observations that can be made and should be part of any landed meteorological package. To be of value, these measurements should be accurate to 0.02% (pressure) and ~1K (temperature). Adding winds to the measurement dramatically increases the constraints that the data set provides to validating models. If the winds are measured with full 3-D resolution, and with adequate sensitivity (5cm/s) and temporal resolution (~10 Hz), then direct eddy fluxes of momentum can be obtained as well. If the temperature is also measured with a fast response instrument (0.5K @ 10Hz), then heat fluxes can also be directly measured. Similarly, if water vapor is measured with enough speed and precision (0.1ppmv @ ~10Hz) then water vapor fluxes can also be directly measured. To complete the “closure experiment” on water stability, the measurement complement should include surface temperature as well as atmospheric backradiation in the form of a boundary layer temperature profiler akin to the Mini-TES instrument on the MER rovers (sensing 0-5km with an accuracy of ~1K). Incoming and reflected solar flux should be measured to 3-5% of the total solar flux at Mars. The dust opacity should also be measured to within 5%. Finally, to achieve the dust electrification measurements, one component of the E-field (preferably vertical) should be measured at 20 Hz, triggered in the presence of passing dust. The sensitivities should be between 0.1V/m and 100 kV/m.

6.1.3.4 Synergies

Landed observations complement the orbital atmospheric observations in several ways. First, the unique perspective of upward sensing column-averaged retrievals of water vapor, ice and dust can be more accurate than orbital estimates of the same parameters because the background is cold sky rather than warm ground. Overflights allow calibration of these quantities between the two platforms. Surface pressure changes with time are indicative of the scale of weather systems in the vicinity of the lander, which can be compared with orbital estimates of weather system structures. Weather phenomena are best observed at the surface where they are strongest, but often difficult to fully resolve from orbit. Combining simultaneous detailed surface observations and global-coverage orbital observations strengthens the depth of understanding available from both data sets. The boundary layer processes that feed into the thermal, dust and volatile transports making climate a key question on Mars are only well observed from the surface. Combining global observations with local observations of forcing and response allows for more confident extrapolation to other locations and epochs.

Such a Next-Generation meteorology package as described here is also a pilot study for future missions that would use trace gas horizontal fluxes to ‘hunt’ sources of biosignatures by following plumes upstream to their source. In order to establish appropriate constraints on the response time of biosignature detectors, we need a better understanding of the turbulent spectrum in the Martian boundary layer. Only by sending capable instruments to Mars can we obtain this knowledge.

Electrical field measurements directly impact our understanding of the lifetime of trace gas species. These effects are only available at the ground on Mars. Combining orbital trace gas observations with surface in situ electrical field/dust measurements can expand our understanding of trace gas interactions with dust.

ATMOSPHERIC SIGNATURES

rev 5/1/07

		SPECIFIC OBJECTIVES	JUSTIFICATION	MEASUREMENT/MISSION REQUIREMENTS	COMMENTS
MEPAG UBERTHEME **GOAL I**: Determine if life ever arose on Mars **Objective A**: Assess the past and present habitability **Objective B**: Characterize carbon cycling in it geochemical context **Objective C**: Assess whether life is or was present	**THEME GOAL** Seek atmospheric evidence for present habitability and life	Identify chemical constituents in the atmosphere that cannot be formed by atmospheric photochemical processes starting with CO_2, H_2O, N_2	No a priori knowledge of what signature to look for and where to look for the signature. As the one opportunity for such a global survey, need to push the sensitivity to the maximum available with current remote sensing instrumentation.	• Broad survey of atmospheric composition—including species containing hydrogen, carbon, nitrogen, oxygen, sulfur, and/or phosphorus atoms • Parts per trillion sensitivities for species with strongest molecular transitions • Sample all latitudes several times each seasons	No measurements, either remote sensing or in situ, will ever rule out the existence of habitability or life even with a highly sensitive negative result, but such a result will place stringent upper limits on possible existence, especially in the near-subsurface.
				• 1 Mars year	
		Locate sources of detected atmospheric signatures of habitability and life	Knowledge of the location of the source region provides direction for later missions. Life may exist that doesn't introduce detectable atmospheric signatures in habitable zones that do produce abiogenic atmospheric signatures.	• Global distribution of water and other detectable atmospheric signatures • Global and vertical distributions of temperature (and winds, if possible), and at least global distribution of dust Horizontal resolution: $<10^4$ km^2 Vertical resolution: ~5 km (~_ scale height) Altitude coverage (goal): sensitivity to lowest scale height	• Tradeoffs between sensitivity, frequency, and spatial resolution of measurements depend on the plume strength and lifetime of plume species seeking to localize. • Concurrent circulation required for use in indirect, inverse modeling for identifying source locations, if these are not detected directly.
		Determine atmospheric lifetimes of signature species	Knowledge of lifetimes is necessary for indirectly locating source region and for characterizing magnitude of source process.	• Global distribution of atmospheric oxidants • Global collocated measurements of atmospheric constituents, temperature, and dust. • Vertical distribution of atmospheric constituents Horizontal resolution: adequate to separate measurements between distinct dust regions Vertical resolution: ~10 km (~1 scale height) Altitude coverage: near-surface – 60 km	Analysis requires understanding to what extent homogeneous and heterogeneous processes limit atmospheric residence times.
		Determine character of process producing signature species. To extent possible, distinguish between abiogenic and biogenic origins.	It may be possible to identify the existence of active biological processes without waiting for in situ analysis or sample return.	• Correlated observations of multiple species and isotopologues at highest practical resolution	It may be possible to determine whether methane, if detected, is or is not being currently produced by some life form. Distinguishing between formation as a result of the decay of remnants of ancient life or from some abiogenic process may not be possible.

ATMOSPHERIC STATE: Orbital Science

rev 5/1/07

		SPECIFIC OBJECTIVES	JUSTIFICATION	MEASUREMENT/MISSION REQUIREMENTS	COMMENTS
MEPAG UBERTHEME **GOAL II**: Understanding the Processes and History of Climate on Mars **Objective A**: Characterize Mars' Atmosphere, Present Climate, and Climate Processes **Objective B**: Characterize Mars' Ancient & Climate Processes through Study of Climate Change **Objective C**: Characterize the State & Processes of the Martian Atmosphere for Safe Operations	**THEME GOAL** Provide new insight into climate processes responsible for seasonal and interannual change	Determine processes controlling the present distributions of water, carbon dioxide, and dust by determining short and long-term trends (daily, seasonal, and interannual) in the present climate. Understand and monitor the behavior of the lower atmosphere (0-80 km) on synoptic scales	Seasonal cycles can change from year to year, particularly as affected by major dust storms. Present climate record is too short to characterize these effects. Meteorological assets maintained in Mars orbit to provide environmental data bases and near real time measurements support planning and implementation of spacecraft arrival and operation.	• Continue climatological monitoring of atmospheric phenomena • Global and vertical distributions of temperature, dust and water • Provide new profiles of atmospheric winds for validation of atmospheric models • Sample the global atmosphere on a daily basis through several seasonal cycles • Temporal Coverage: -- 1or more Mars years -- Temporal sampling that separates diurnal and seasonal cycles • Profile Resolutions / Spatial Coverage: -- Vert. resoln. goal: ~5 km (~1/2 scale ht.); Min. required: ~10 km (~ 1 scale ht.) -- Temperature & dust 0 – 60 km -- Water vapor: 0-20 km (esp. < 10 km) -- Wind measurements: 10 m/s precision with ~10 km vertical resolution, 5-60 km in altitude range • Climatological monitoring: -- Synoptic-scale imaging with ability to distinguish atmospheric dust and condensates -- Frequent near-global coverage	• Year-to-year variability and long-term trends are assessed by building on the nearly continuous climatological records started with MGS and now being extended by MRO. • Reproducing seasonal and interannual variability is a major validation of atmospheric models and numerical simulation of climate processes. Model validation requires measurements that capture both radiative forcing and atmospheric response. • Present measurements of temperature, dust, and water are compromised by inability to cleanly separate the retrieved quantities in the thermal IR. • A new element would be measurements (beyond thermal IR) that minimize the effects of dust and condensates on temperature and water vapor measurements. • A new element is provided by wind measurements that provide an independent check when validating atmospheric circulation models.
		Search for micro-climates	Knowledge of the location of exceptionally warm or wet locales, exceptionally cold locales, or areas of significant change in surface volatile or dust reservoirs provides direction for later missions.	• Global distribution of water and other detectable atmospheric signatures • Observations of surface albedo and composition, including changes in the seasonal and permanent polar caps.	Regional detection and mapping of water vapor or other trace gases can be used to identify source locations through inverse modeling, validated by atmospheric state and circulation measurements.
		Characterize the stratigraphic record of climate change in part by understanding processes controlling transport and deposition/removal of water, carbon dioxide, and dust.	Characterizing the record represented by layering in the polar regions and perhaps elsewhere requires knowing what controls the frequency of major dust storms.	• Addressed partly by (1) above	To address this objective fully would require quantitative estimates of changes in volatile mass or energy budgets. These measurements are not accomplished by the proposed payload (see Existence Proof).

ATMOSPHERIC STATE: Landed Science

rev 5/1/07

	SPECIFIC OBJECTIVES	JUSTIFICATION	MEASUREMENT/MISSION REQUIREMENTS	COMMENTS
THEME GOAL Understand Martian Boundary Layer Processes, Water/Volatile Cycling/Stability and dust electrificatioon	Characterize boundary layer mixing processes.	Boundary Layer mixing controls surface/atmosphere exchange of heat, momentum (i.e. Aeolian processes) and volatiles.	• 3-D, fast response, high-accuracy winds, resolving turbulent eddies. Directly yields momentum flux. (5cm/s @ 10 Hz). • Fast response temperature sensor for heat fluxes (0.5K @ 10Hz) • Fast response, accurate hygrometer for water vapor fluxes. (0.1ppmv @ 10 Hz) • 10 minute averages reported hourly all day	• Meteorological observations with more sophistication are needed to allow further refinement of our understanding of and ability to model the processes occurring in the Martian boundary layer. • Mesoscale models cannot be fully validated with existing data types. Greater richness in the data set is required to provide adequate constraints on the models to validate them.
	Understand processes controlling stability and exchange of water vapor between surface and atmosphere.	To extrapolate from localized observations to other places and other epochs, the *processes* that control volatile stability and transport must be well understood.	• Incoming & reflected solar (to 3-5% of total solar flux at Mars) • Surface temperature (to 1K) • Atmospheric back-radiation, height of unstable boundary layer (0-5km, to 1K) • 10 minute averages reported hourly all day	It is not enough to characterize the distribution of water vapor, as many factors influence this. Much more powerful to monitor the forcing functions influencing it, and simultaneously document the response. A “Closure Experiment”.
	Monitor weather and climate from a unique location on Mars	Weather is best observed from the surface, remote sensing struggles to reveal this region. Different locations allow constraints to be placed on global modeling of atmospheric dust distribution, thermal tide responses, zonal winds and the seasonal changes of all of these factors.	• Pressure to 0.02% • Temperature to 1K • Dust opacity to 5% •10 minute averages reported hourly all day	This is the more traditional approach to a Met Station at Mars, and by itself represents incremental science with less impact than the other objectives. However, to have any value, the instruments must be well designed to optimally function in the Martian environment, and above all well-calibrated and insensitive to confounding factors.
	Monitor and record extreme weather events from the surface	Extreme events such as dust devils and dust storms, or even just high wind events may be hazardous to people or rovers and landers at Mars. On the other hand, events like these may be harnessed to clean dust from solar cells if properly understood.	• Pressure, Temperature, High precision Winds and Radiative and Thermal Forcing as indicated above, but with fast response on P, T and forcing as well (~1Hz). •Triggered to record high temporal resolution data on indication of an extreme event.	Monitoring extreme events alone does not allow much deeper insight into the controlling factors that create them. Engineering considerations might be satisfied with basic observations, but again, the ability to extrapolate to other locations with different conditions requires observations not only of the meteorological response, but also the forcing functions that drive it. A complete Met package is required to return fully useful data.
	Measure the Electric Field from passing saltating dust, dust devils and dust storms	Dust electrochemistry, as a newly realized atmospheric chemistry pathway may be important to the lifetimes of methane or other trace gases.	Measure 1 component of the E-field, preferably vertical between 0.1V/m and 100 kV/m. Sample at 20Hz, quasi-continuously or triggered in the presence of passing dust.	Without in situ observations of the dust electrification effects, modeling efforts are stymied, and significant effects on trace gases may remain poorly understood.

6.2 *Polar Processes and Modern Climate*

6.2.1 Background

The modern Martian record of volatile reservoirs and their dynamics is uniquely manifested in the polar regions. The NRC Decadal Survey (2003) has suggested that a more complete understanding of the sources and sinks of major volatiles systems within the Solar System is a potentially paradigm-shifting priority across the next decade of planetary exploration. This overarching objective ties the modern record of climate to the migration pathways within the accessible Mars "system" of primary volatile species, including CO_2 and H_2O. It also serves as the context within which to document and quantify climate variability and the modern history of water in three dimensions, which links it directly to MEPAG priorities within Geology and Geophysics. Given the role of volatile reservoirs in the broad theme of "habitability", pursuit of polar processes and climatology is of significant importance in the science of Mars.

The most likely location of a preserved record of recent Mars climate history is contained within the north and south polar deposits and circumpolar materials. The polar layered deposits (PLD) and residual ice caps may reflect the last few hundred thousand to few million years, while terrain softening, periglacial features, and glacial deposits at mid to equatorial latitudes reflect recent high obliquity cycles within the last few million years. Dune and mantling deposits around the northern PLD span the entire Amazonian period, ~ 3Ga to the present, and multiple sequences of deposition and erosion are recorded. Understanding the interaction between the current climate and current residual ice caps will act as a 'Rosetta stone' which we can use to interpret the layered deposits in terms of the previous climates which formed them.

Recently, five high level questions with regard to polar processes have emerged from the polar community and were considered and revised by the SAG-2. These are:

1) What are the mass & energy budgets of both seasonal and residual volatile deposits, and what processes control these budgets on seasonal and longer timescales?
2) How do volatiles and dust exchange between polar and non-polar reservoirs? How has this exchange affected the past and present distribution of surface and subsurface ice?
3) What are the physical characteristics of the polar deposits and how are the different geologic units within, beneath, and surrounding the PLD related?
4) What chronology, compositional variability, and record of climatic change are expressed in the stratigraphy of the PLD?
5) How old are the polar-layered deposits? And what are their glacial, fluvial, depositional and erosional histories?

We briefly summarize current polar and climate processes from seasonal to longer timeframes and consider what critical new measurements MSO can make to contribute to these questions.

6.2.1.1 Seasonal polar ice caps

The current Mars climate is driven by the advance and retreat of the seasonal polar caps, with approximately 25% of the atmosphere condensing into the caps during autumn and winter and sublimating back into the atmosphere in the spring. This annual process is controlled by the net energy balance of absorbed insolation and thermal radiative losses to space. Net energy can be stored in the ice rich regolith, laterally transported by the atmosphere, or converted to/from the latent heat of fusion for CO_2 ice. The lateral transport of heat in the atmosphere associated with seasonal cap formation and ablation is not well constrained and could be quite large, depending on the location and season. The atmospheric transport contribution may be the same order of magnitude as the heat storage contribution from an icy regolith.

The edge of the advancing cap is typically 10 degrees of latitude equator-ward of the edge of polar night. This means that the dominant processes that control the condensation of the cap occur within the polar night, a region that is invisible to passive visible and near infrared cameras and spectrometers. Early spacecraft thermal observations of the seasonal caps revealed brightness temperatures significantly lower than the expected kinetic temperature for CO_2 ice in equilibrium with a CO_2 atmosphere. These cold areas or spots were typically a few hundred kilometers in diameter, with 20 μm brightness temperatures as low as 130K and typical lifetime of a few days. The cold spots may be freshly deposited CO_2 snow, CO_2 condensates high in the atmosphere (clouds), or "dry ice blizzards". While the "dry ice blizzards" are short-lived, the snow that remains can be observed as cold spots for up to several weeks, thus affecting the long-term energy balance. MOLA, TES, and radio science experiments agree that the polar night of both polar caps have significant CO_2 cloud cover, which also affects cap condensation. The exact effects of these processes on the energy balance are still poorly constrained and additional observations are needed.

The distribution of seasonal CO_2 ice provides information about the interaction between the atmosphere, topography, and surface properties. The density of the CO_2 ice constrains several important polar processes, including deposition mechanisms and densification. Measurements of density are more uncertain than mass, owing to current uncertainties in linear thickness measurements and comparisons between regionally averaged frost values and local measurements provided by MOLA. Current estimates of seasonal CO_2 ice densities vary from 500 kg/m^3 to 1200 kg/m^3 depending on location and technique used.

Critical new measurements to be made regarding the seasonal caps include the polar night energy balance, density of the seasonal cap, and volatile and dust transport in/out of the Polar Regions. Energy balance is addressed through surface and atmospheric temperature and albedo measurements. An active laser system can be used to determine cloud condensation altitudes coupled with concurrent thermal measurements during the polar night. Thermal spectroscopy and bolometry provide temperature as a function of altitude in the condensing atmosphere as well. Density of the seasonal cap is determined by precise measurement of cap volume coupled with mass estimates of CO_2 in exchange with the atmosphere. Volatile and dust transport are monitored with visible imagery and through compositional mapping.

6.2.1.2 Residual polar ice caps

The southern residual CO_2 cap is finely layered and typically a few tens of meters thick. As has recently been discovered by THEMIS and OMEGA this CO_2 veneer is underlain by water ice. Changes in the appearance of the residual ice between the Mariner 9 and Viking missions and modeling of "swiss cheese" formation via sublimation suggest this upper CO_2 layer could be less than a few thousand Martian years old. Observations of expanding pits have prompted suggestions that this reservoir of CO_2 ice is rapidly shrinking implying current climate change. The highly inclined walls of these pits are expanding at rates of up to 5m/year; however, without understanding the mass balance of the intervening flat surfaces it is impossible to discern whether the residual cap as a whole is gaining or losing CO_2 ice, a gap in our current understanding. This small reservoir of solid CO_2 buffers the atmospheric pressure and so, in part, controls the current climate. CO_2 ice is considerably more volatile than water ice, and the southern residual cap responds sensitively to any change in climatic conditions; thus, understanding the mass balance of this deposit not only informs us about the climate of today but also that of the recent past and near future.

In the north, the problem is somewhat different. The residual water ice cap is lower in albedo, compared with the south, implying both older, coarser ice and more dirt contamination. The finest layers observed are near the resolution limit of currently available imagery. OMEGA data have recently indicated that there is a strong component of water ice in the seasonal frost and that this seasonally deposited water frost is sublimated after the CO_2 and by mid-summer exposes old, large-grained ice to ablation. Recent studies using TES have shown highly variable albedo and frost migration patterns during the northern summer. Frost migration has both a large-scale pattern that repeats annually and subtle small-scale features that are highly variable from year to year. Frost mobility and seasonally sustained fine-grained ice may represent a complicated spatial pattern of accumulation and erosion occurring throughout the residual water ice cap. Constraining the current deposition and erosion rates is needed to provide a powerful boundary condition on the availability of water vapor and also link the observed layers to annual or longer climate cycles.

Critical new measurements to be made with regard to the compositionally distinct residual ice caps include: residual cap volume, mass balance, time variability of albedo and composition, slopes related to flow and relaxation, and small changes in volume with time. Multi-temporal measurements of the cm-scale topography of both the seasonal and residual polar caps can now be achieved via orbital multibeam laser altimetry. This will address both volume and mass exchange with time as well as a high-resolution assessment of slopes. Albedo and composition need to be monitored with better time resolution than MRO, observing the entire cap within a few degrees of Ls. Such monitoring can occur at selected optical, near-infrared and thermal infrared wavelengths, chosen specifically to distinguish water and CO_2 ices as well as non-ice components.

6.2.1.3 Polar Layered Deposits (PLD)

Since the layers within the PLD likely contain the best-preserved record on the planet of recent Martian climate history, understanding their stratigraphy is important. While rough stratigraphic correlations can be obtained through the use of MOC images tied with MOLA altimetry, MOLA data do not provide accurate enough estimates of layer elevation. Higher spatial resolution/vertical accuracy elevation data are needed which can then be tied more accurately with existing imaging data sets. Even existing imaging data sets are insufficient to fully characterize PLD stratigraphy. Previous experience demonstrates that only a select few of the available images may be suitable for layer correlation and hence, while past image data sets will certainly carry us closer towards a fuller characterization of PLD stratigraphy and are a necessary first step, more high resolution image coverage is necessary for a complete understanding. Indeed, cm-resolution topographic correlation of PLD layers across the full extent of the polar cap system may allow an improved assessment of the history of this important system, and facilitate assessment of individual layer volumes (and hence deposition rates).

The records in both PLD have been modified over their history by several processes. The significance of ice flow in modifying the overall internal layer structure of at least the NPLD is likely to be negligible, but understanding its impact on small-scale structure (such as localized deformation) is necessary to allow this record to be fully interpreted. Flow velocities are also interpreted to be higher at marginal scarps and other steep slopes, possibly competing with sublimation in forming the overall shape of both polar domes. Crater morphologies on the layered deposits may also be the result of viscous relaxation of the target material, and relaxation may remove craters, falsely decreasing the apparent surface age derived from crater counting. Radar sounding of layer shapes around craters will reveal the extent to which they have viscously relaxed. A detailed surface topography model (with extremely high vertical accuracy) will also be needed to accurately model crater shapes. PLD shapes derived from multi-beam laser altimeter data more accurate than those from MOLA will also allow us to better constrain flow models and to better test for the effects of flow on steep margin scarps.

The surface of the south polar layered deposits is mantled with a cohesive but low thermal inertia material, which is likely to be a sublimation lag deposit. The thickness of this mantle is unknown and may vary considerably throughout the region. However, locations where it is only millimeters thick (where the thermal signature of the underlying water ice shows through) have recently been discovered. Younger ice/dust/frost deposits also appear to mantle the layers exposed in the NPLD troughs, masking their inherent albedo. Such thin lag deposits can impact energy balance due to the different thermal inertia of the underlying ice.

6.2.1.4 Mid-latitude Glacial and Periglacial deposits

Meters-thick ice-rich deposits, in latitudinally dependent states of continuity or degradation, drape pre-existing topography poleward of 30°. The presence of these youthful deposits can be explained by redistribution of polar volatiles by orbitally driven climate change over the past 3-5 million years. The suite of ice related features are the most well preserved record of Mars climate processes affecting the mid-high latitudes, and it is essential to understand this record to constrain how volatiles are cycled among surface reservoirs. A more complete understanding will have important implications for assessing recent habitability and defining resource availability. To better constrain the volumes of ice contained within the mantle, we need accurate measurements of its thickness, best provided by high vertical accuracy topography. Furthermore, there is abundant evidence for glacial and periglacial deposits and features in mid latitude and equatorial regions (e.g. tropical mountain glaciers) pointing to even more vigorous redistribution and cycling of volatiles in the earlier Amazonian. To better understand the amounts of ice implied by these features and their evolution through time, we need to know the volumes of the glacial deposits and their slopes as measured from high spatial resolution/high vertical accuracy topographic data. Such measurements will allow for better-constrained modeling of glacier shape and how that shape relates to climate. Imaging radar data would create access to the morphological aspects of non-polar ice features that are often covered by dust.

6.2.2 Priority Goals and Measurements

The SAG-2 considered areas where MSO observations of the polar, glacial and periglacial terrains would enable major advances in the understanding of the current and previous Martian climate. In the context of recent discoveries and outstanding issues describe previously a series of new priority measurements were defined. These are:

1) Thickness, volume and slopes of seasonal, residual, PLD and lower latitude glacial deposits.
2) Changes in volume of volatile deposits as a function of location and season.
3) Density of seasonal ice deposits as a function of location and season.
4) Mass and energy balance through albedo, temperature, composition, topography, atmospheric transport, and polar night processes. High time resolution observation in variation of these properties.
5) Stratigraphy of PLD and residual ice, particularly the upper few 10's of meters not accessible to MARSIS and SHARAD.

Extremely high vertical resolution topographic data (i.e., few cm) can be used to map both seasonal and permanent deposits in three dimensions and to correlate them across wide regions at sub-meter vertical scales. High-resolution imagery will help us to interpret the stratigraphic information we compile in terms of previous climate regimes. SAR (and related nadir-SAR "sounding") can be used to 'see through' lag deposits, which currently covers much of the PLD and also to characterize individual layers' scattering properties. In order to more definitively tie the preserved layer record to past climate changes, an understanding of the current residual cap energy balance (at both poles) and its relationship to current atmospheric dynamics and orbital parameters is necessary. No other existing (MEX, MRO, Mars Aeronomy Orbiter) orbital remote sensing approach can provide this unique information. Proposed priority measurements could profoundly impact the state-of-knowledge in this area. As such, the proposed measurements would tie non-polar latitude evidence of polar processes (tropical mountain glaciers, periglacial landscapes, mantling deposits) to global evolution of the planet within differing climate regimes. This could relate the history of atmospheric density to climate variability and thereby improve GCM fidelity.

6.2.2.1 Topography and deposit volume

Increased spatial resolution topographic measurements are expected to provide constraints with regard to the seasonal and residual CO_2 ice, accurate volumetric measurements of the PLD and residual caps, and characteristics of mid- to high-latitude glacial and periglacial mantled deposits. Quantifying the seasonal cycle of CO_2 frost in 3 dimensions will facilitate the identification of the timing of the onset of erosion between seasonal and residual ice in the south. High-resolution measurements of elevation changes (or lack thereof) will permit determination of the extent and direction of changes in the current atmospheric pressure and, by extension, the climate. High-resolution topography can constrain the seasonal cap volume and by measuring mass exchange with the atmosphere constrain the cap density. Higher resolution topography will identify unusually high surface slopes, providing critical information for flow and relaxation models of these features. As the PLD are the expected source of mid to high latitude deposits, concurrent measurement of the volume of the PLD and of these glacial and periglacial features will provide constraints on the amount of water exchanged at different obliquity periods.

Multi-temporal measurements of the cm-scale topography can now be achieved via orbital multi-beam laser altimetry. Monthly gridded measurements of the geodetic topography of the polar regions can now be achieved with 3-5 cm (RMS) vertical accuracy at horizontal scales as fine as 100m. By measuring the monthly topography of the polar cap systems on Mars high-precision measurements of the differential volume of volatiles can be made, at 100 times the resolution demonstrated by MOLA. Such measurements can be integrated into volume estimates and the volume change on a seasonal basis can then be quantified and compared against MGS-era estimates. All of these measurements fully resolve the spatial properties of the polar cap system at ~ 100m horizontal scales, and as such can be coupled to energy balance measurements at similar horizontal and spatial scales. A simple Radio Science Experiment (RSE) employing an Ultra-Stable-Oscillator (USO), as on MGS, can be used to measure the mass of CO_2 in the atmosphere. Using these mass and volume measurements density of the volatile deposits can be estimated. Continuation of such measurements across the polar night and independent of the polar hood and other cloud-cover phenomena will produce a highly time-resolved sample of the mass exchange dynamics of the polar and atmospheric volatile reservoirs.

High-resolution multibeam laser altimeter measurements of PLD, glacial and periglacial deposits can resolve their three-dimensional character, allowing their volumes (and masses) to be assessed. New information on layer geometries and volumes across the entire expanse of the deposits can be made. This will provide the context within which continuing sub-meter imaging can be used to develop quantitative models of the salient processes responsible for PLD formation and destruction. In addition, the geodetic quality of the measurements will allow detailed estimation of individual layer or layer bundle volumes, even in cases where portions of the layers are buried. Such volumetric measurements can then be tied to mass flux estimates that link the PLD to mid-latitude glacial features and ultimately to processes related to climate variability.

The layer volume measurements can be amplified by including observations of the shallow layering structure of the polar caps by means of various active microwave methodologies, including long-wavelength multipolarization SAR (i.e., at L or P-bands), or via high-bandwidth nadir SAR observations processed using Delay-Doppler methods to facilitate shallow layer "sounding". These methods could provide sub-meter layer imaging or ranging observations at scales as fine as 100m across the polar cap systems on a seasonal basis. Such measurements would bridge the gap between VHF sounding radar observations from MARSIS and SHARAD, which cannot resolve the fine-scale (i.e., sub-meter) vertical layering structure within the polar caps within tens of meters of the surface.

6.2.2.2 *Mass and Energy Balance*

Early estimates of energy balance assumed that the regolith had a sufficiently low thermal inertia so that heat storage of the regolith could be neglected. Most energy balance studies have followed this example. The discovery of the presence of high concentrations of near-surface H_2O ice at high latitudes has brought into question the assumption that the regolith can be ignored in energy balance studies. In fact, the energy balance, and thus the accumulation of seasonal CO_2, can be greatly affected by the presence of surface and near-surface ice. H_2O ice stores a significant amount of heat during the summer and then releases this heat during the fall, delaying the formation of the seasonal CO_2 and reducing the net accumulation. Most energy studies have also been 1-dimensional models, and therefore implicitly ignore atmospheric transport of heat. GCMs, which include atmospheric transfer of heat, have yet to fully implement effects from high thermal inertia regolith in the polar regions. A space-borne platform, with a suite of instruments that measure nearly all aspects of the energy balance in the polar regions can be used to constrain atmospheric transport and provides an independent validation of Mars GCMs.

A detailed analysis of the polar energy balance will provide a better description of the stratigraphy of the near surface regolith to include thermal inertia, water ice content, and depths to the ice table. Heat transport will be inferred from the residuals of the polar energy balance and compared to GCMs. Atmospheric dynamics and transport plays a significant role in the formation and dissipation of the polar caps, perhaps even being the cause of both the SPRC offset and the location of the Cryptic region. Determination of the energy balance is achieved through thermal and vis/NIR observations for albedo and temperature with time. Thermal and vis/NIR observations will enable our ability to constrain the local column abundance of CO_2, the composition, stratigraphy and thermal properties of the regolith, the solar energy absorbed by the surface, and the thermal energy lost to space. Thermal inertia is derived from seasonal temperature curves and coupled with estimates from GRS can constrain the depth to the water ice. The mass balance between the atmosphere and the polar caps can be assessed as described in the previous section using high-resolution topography and radio science estimates of mass. Crucial to the energy absorption is identification of water content in seasonal frost and dust content in residual ices. This measurement is achieved through high temporal sampling at selected near-infrared wavelengths.

6.2.2.3 Stratigraphy and Mantling

A key goal will be to correlate the layers within both PLD and to discern the relationship between stratigraphy and the climatic record. This will be accomplished through high-resolution imagery and altimetry, compositional mapping and determination of near-surface layers and mantle deposit thickness using SAR imaging and sounding techniques.

Correlating exposures of individual, thin layers and packages of layers visible in high resolution imagery will facilitate mapping each layer in three dimensions, as has been performed at lower resolution using MOC, MOLA, and THEMIS data in both the north and south. This can be extended by an order of magnitude using the combination of sub-meter imaging together with cm-precision multi-beam laser altimetry. Similar techniques can be used to more accurately and much more thoroughly correlate better-defined layers using additional data. HiRISE is capable of resolving the thinnest layers visible from orbit, but the coverage of the layers will likely not be enough to definitively characterize polar stratigraphy. Rather, HiRISE will provide a sample, which may or may not be representative, especially given localized controls on deposition (microclimates). Thus, more high-resolution image coverage by MSO will be necessary for completing layer correlation studies. High spatial resolution topographic data is needed to link the layers observed in images with their elevations so that one can create a 3D map of layer stratigraphy. MOLA data is insufficient for the task, and only just barely useable in connection with MOC images. While HiRISE may provide some stereo coverage from which high resolution DTMs can be produced, such coverage will be sparse, and a comprehensive stratigraphic study of a region as large as the PLD cannot rely on labor-intensive stereo DTM production alone. While SHARAD and MARSIS provide some valuable insight into the internal structure of the PLD, they cannot resolve layers visible in images. Higher vertical resolution radar data would be extremely useful for tracing layers exposed in trough walls beneath the flat, between-trough areas where layers are not exposed at the surface.

High-bandwidth SAR instruments can now be operated in creative new modes, thereby facilitating measurement of sub-surface layering at sub-meter vertical scales. Nadir SAR sounding using high-bandwidth systems and delay-Doppler processing methods can now be used to resolve layers only 70cm thick within the uppermost tens of meters of ice deposits. Based on existing, low-resolution MARSIS and SHARAD results, these techniques can be expected to penetrate 10's of meters in the Martian polar regions. This could provide spatially resolved maps of the stacks of layers within tens of meters of the surface at scales as fine as 100-200m (horizontally) and allow correlation of these buried layers with exposures in troughs, reentrants and at the cap edge. In addition, buried layer continuity can be probed across scales as wide as the residual caps themselves. This would result in gridded datasets from which measurement of volumes can be achieved. Such volumetric measurements can be used to estimate layer thicknesses and shapes below the surface. There is likely to be a density contrast between seasonal and residual CO_2 frost (perhaps by a factor of 2-3), so there may be a reflection from this interface as well as the surface-atmosphere interface that can be used to quantify the seasonal frost thickness. Penetration of thin mantling deposits is anticipated via classical SAR imaging methods, which can separate these deposits from the larger fraction of the PLD. Such measurements could feed-forward to missions that directly sample the shallow subsurface of the caps themselves. Comparisons of the thermal, morphologic, and topographic properties of the residual ices with those of the layers in these deposits can be used to further constrain the details of the state and composition of this material. In this way the climatic record in the polar layered deposits can be completely characterized in three dimensions and at scales appropriate for sub-regional modeling (sub-km).

Table 6.2 Polar Goals Matrix

Polar Themes	Specific Objective	Measurement Required	Potential Instruments	Issues/Comments	Justification
What are the mass & energy budgets of both seasonal and residual volatile deposits, and what processes control these budgets on seasonal and longer timescales?	Mass, density, and volume of seasonal CO2 Ice in time and space. Volume of water in north seasonal cap.	High resolution topography, of order cm plus time resolution of a few degress of Ls	Laser Altimeter (multi-beam for increased crossovers to ensure 1-3 cm RMS vertical accuracy)		Polar regions show strong seasonal and interannual variability. Seasonal exchange drives the water cycle in the north. That cycle drives where permafrost regions will be found with impact to future sites of astrobiological potentential. Seasonal CO2 thickness is unconstrained with implications for ground ice cover to be encountered by future polar landed missions.
		Seasonal mass of the atmosphere in exchange with the surface.	Radio Science with ultra stable oscillator		
		Synoptic observations to map H2O/CO2 areal extent, composition and temperature with high time frequency (entire cap area every few days)	Multi-spectral SWIR+TIR SWIR: ~100m spatial, 30 spectral channels TIR: ~3km spatial 10 spectral channels, plus vis and tir bolometers. Cross-track coverage ~100-500km		
	Accumlation/Ablation rates and monitoring of residual ice (north and south)	Spectral observations and high spatial resolution imaging to map frost and residual ice grain size and morphology evolution with time.	Multi-spectral SWIR+TIR SWIR: ~100m, 30 channels TIR: ~3km 10 channels, plus vis and tir bolometers. Cross-track coverage ~100-500km	Will be addressed in part by MRO	Determining current rates of erosion (south) and accumulation or erosion (north) is critical to linking observed stratigraphy to long-term climate record. A non-CO2 south residual cap strongly alters total energy balance of the system.
		High spatial resolution imaging of any possible scarp (south) and polar trough (north) retreat.	HiRISE class imaging+stereo		
		High vertical accuracy monitoring of PLD height over several years.	Imaging SAR or LIDAR with capability to detect surface height changes of 1 cm over several years.		
How do volatiles and dust exchange between polar and non-polar reservoirs? How has this exchange affected the past and present distribution of surface and subsurface ice?	Monitor energy exchange during polar night to understand condensation processes (snow vs slab ice).	Thermal or active NIR/SWIR measurements sensitive to CO2 presence and state.	Multi-spectral TIR or laser reflectivity		Type of surface ice and processes impact energy balance with climate feedback.
	Identify transport of water in and out of polar regions	High spatial and temporal monitoring of water vapor in atmosphere.	High spectral/spatial resolution atmospheric sounding (I.e. FTIR). Passive microwave or mm wave.	Synergy with "Atmospheric state" goals.	Global water budget and transport will remain critical questions post MRO.
	Formation and longevity of sulfates in circum-polar dune field.	Spectral observations and high spatial resolution imaging to map extent of deposits and evolution with time.	Multi-spectral SWIR+TIR or Hyperspectral plus HiRISE class imaging.	Will be addressed in part by MRO	New discovery from OMEGA, long term stability and causes need to be understood in terms of global sulfur cycle.
	Determine near-surface wind velocities as a function of season.	Winds +/-10% at 200km spatial, 2km vertical scales.	Sub-mm spectrometer	Synergy with "Atmospheric state" goals.	Provides independent check on circulation models.
	Identify dust content of residual ice deposits.			Some constraints by MRO through SHARAD and CRISM. Desire for in-situ determination.	Dust content determination will impact volatile budget and inventory.
	Dust transport in and out of polar regions.	Synoptic color imaging for dust vs ice transport. Atmosphere Temp sounding.		Synergy with "Atmospheric state" goals.	Continuous climate monitoring.
	Link present accumulation/ ablation to observed stratigraphy	Increased spatial coverage with high spatial resolution imaging.	HiRISE class imaging+stereo	Synergy with geology	Current climate cycles will determine extent of record inferred in cap as a whole.
		Long term evolution of residual cap topography on order cm vertical scales.	SAR interferometry to view surface displacement or Laser Altimeter	Synergy with geology	
What are the physical characteristics of the polar deposits and how are the different geologic units within, beneath, and surrounding the PLD related?	Constrain porosity, compaction and thermal inertia.	Surface temperature monitoring at times other than MGS and Odyssey, e.g. noon to 1pm.	Multispectral thermal + vis and tir bolometers.	What we can do from orbit will be well constrained by MRO.	Physical characteristics are poorly known and have large impact on energy balance. May be cause of enigmatica phenomena such as cryptic region and geysers. Observations used to constrain climate models.
	In-situ measurements of pressure, temperature, winds, thermal inertia at multiple locations with monitoring of seasonal changes in these values.			The group does not advocate use of the DOP for this objective as multiple sites are needed.	
	Further characterization of morphology	Continued high spatial resolution imaging	HiRISE class imaging+stereo		
What chronology, compositional variability, and record of climatic change is expressed in the stratigraphy of the PLD?	Identify the stratigraphy of the uppermost few hundred meters to understand recent oscillations in deposition history.	Link layers visible in troughs across entire residual cap area and interior. Probe interior structure (away from troughs) at <1m vertical resolution.	HiRISE class imaging+stereo	Synergy with geology	Link recent climate record to calculated obliquity and other known climate forcing cycles.
			High resolution sounding imaging radar	Synergy with geology	
How old are the polar layered deposits? And what are their glacial, fluvial, depositional and erosional histories?	Elemental and isotopic ratios relevant to age (e.g. D/H)			To get beyond MRO to address this theme need to land and drill, melt or traverse stratigraphy. Which is clearly beyond MSO.	Absolute chronolgy is undetermined, needed to constrain timing and history of aqueous processes and martian evolution.
	In-situ measurements of grain size, dust content, composition and extent of layers				
	Morphological, compositional, and physical evidence for glacial flow and/or melting		Addressed in part by MRO HiRISE/CRISM.		

6.3 *Geology: Near-surface Science*

6.3.1 Overview

In response to the SAG-2 charter element regarding orbital geophysics, the "geology" sub-group was tasked to develop scientific questions, consistent with the MEPAG goals document of February 2006, and to propose feasible instruments that can accomplish the corresponding investigations. A second charter element focused on the major drivers for a high resolution imaging system on MSO, particularly with regard to landing site planning. The geology sub-group developed a number of investigations under the broad themes of "Ancient Environments" and "Dynamic Mars/Mars Today" (Table 6.3). These investigations address major scientific questions, responsive to the MEPAG document and having a high degree of feed-forward for future mission planning.

In order to provide a meaningful basis for comparison and prioritization among the SAG-2 sub-groups, scientific investigations developed by the geology group are directly correlated with one or more MEPAG-recommended areas of study. Two over-arching theme areas emerged from this effort:

(1) Ancient Environments – This theme reflects primarily the MEPAG interest in locating and characterizing the geologic signatures of conditions that may have provided habitable settings, and in understanding how these conditions varied with space and time.

(2) Dynamic Mars/Mars Today – This theme reflects primarily the MEPAG interest in the current state and distribution of water across Mars, rates of change due to various processes, and the location of areas of remnant thermal or tectonic activity.

Within each of these areas, the sub-group developed a number of scientific investigations to address questions that remain after recent or ongoing orbital and landed missions (Table 6.3).

6.3.2 Ancient Environments

Results from the Opportunity rover traverse and mineralogy maps from the OMEGA and CRISM instruments suggest that "habitable" conditions existed in various locales for limited periods of time. Understanding the duration and extent of these conditions based on the geologic record is a key MEPAG goal. Two complementary major investigations for MSO are proposed.

The first approach emphasizes greater visible image coverage, at the highest possible spatial resolution, of layered bedrock exposures linked with sedimentary depositional environments. With sufficient resolution (e.g., 5-10 cm per pixel), these observations could augment the much more localized observations of surface rovers in revealing potentially habitable settings. Group discussion, however, suggests that increased coverage at the image spatial resolution consistent with current capabilities (~30 cm per pixel) could also address many of these investigations. The well-exposed sedimentary deposits cover extensive areas, while HiRISE on MRO can cover <1% of Mars at full resolution in the nominal mission. The alternative approach of using very high spatial-resolution (e.g., 1-2 m per pixel) synthetic aperture radar data was not deemed practical to satisfy the surface imaging science requirements. At a lower priority level to the high-resolution imaging goal is an interest in the mineralogy of layered or possible water-formed deposits at much higher spatial resolution (e.g., a few meters per pixel) than currently available from orbit.

The second approach emphasizes mapping of the near surface geologic record to reveal the morphology of bedrock buried by meters of sediment, and to thus define the extent and stratigraphy of units associated with limited outcrops of layered or compositionally significant (e.g., phyllosilicates, sulfates, carbonates) materials. The near-surface geologic record may also contain evidence of process-specific landforms (lava flow fronts, deltaic fans) not evident from visible imaging.

For example, some sequences of the light-toned layered rocks studied by the Opportunity rover likely formed in the presence of running water. Whether these deposits reflect deposition in habitable environments is a topic of ongoing discussion, but a crucial outstanding question is their spatial extent beneath widespread mantling materials. Mapping of the upper bedrock surface below the mantling deposits will reveal the extent of the sedimentary rocks, and place constraints on the extent of the aqueous environment in which they formed. In other locations, an interpretation from OMEGA results is that there was a sequence of climatic periods during which phyllosilicates formed early, followed by sulfates. These indicators of ancient climate are known only from limited outcrops where their spectral properties can be measured. Subsurface imaging from orbit of the bedrock geomorphology will reveal the extent and modification of materials seen in outcrops, and expand our knowledge of the size and distribution of potentially habitable environments.

No existing remote sensing data uniquely map the thickness of surficial sediments across Mars, but there are studies that suggest the range of depths. For example, the MER and MPF rovers and earlier Landers reveal outcrops of bedrock, and small craters, that are buried by less than a meter of fine material. Orbital images show abundant examples of sediment-muted terrain features (i.e., small impact craters) that imply a thickness of no more than several meters. The thicknesses are more directly revealed at the edges of steep slopes, for example associated with craters or troughs, but this provides spotty information. Earth-based radar data detect rugged lava flows covered by sediments that must be less than a meter or two thick. Finally, thermal inertia studies show that many “dusty” areas have some component of exposed bedrock or surface blocks, consistent with sediment thickness of tens of cm to a few meters. Based on this evidence, 3 m is a conservative upper estimate of mantling deposit thickness over many features of interest.

6.3.3 Dynamic Mars/Mars Today

Known activity on Mars includes seasonal cycling of polar cap deposits, longer-term changes in the residual caps, aeolian movement of fine material, downslope debris movement, a slow accumulation of small impact craters, and possibly discharge of water in very limited settings. These changes can be identified in long-term imaging, and quantified through detailed stereo mapping or other techniques. Many of the processes observed on Mars have not been fully characterized, such as the southern residual cap retreat, the global cratering rate (flux), aeolian sources and sinks, and the occurrence of slope-related features that could be formed by water. Some features of the current Martian water inventory remain elusive, such as the detailed distribution of near-surface ground ice partially mapped from hydrogen abundance. Other processes that may occur, such as ground changes due to ice sublimation, tectonic motions, or thermal uplift/subsidence, have not been constrained by any measurement to date.

The SAG-2 sub-group developed a varied list of science investigations to address these outstanding issues (Table 6.3). These investigations emphasize the role of water at and near the surface by ongoing visible-image monitoring of slopes where discharges may occur and sites of change in the residual caps, and by seeking a detailed spatial characterization of ground ice at high latitudes. In a more global vein, investigations will seek evidence of modern ground motion due to endogenic processes, measure the rate of cratering as a guide to relative age dating of surfaces on Mars, and characterize the rates and general sources and sinks for weathering processes.

Surface visible imaging at the 30 cm / pixel scale, with the capability to acquire stereo-compatible pairs for detailed local topography, satisfies many of the goals of targeted monitoring of surface change (e.g., in the residual caps and gullied slopes). Wider-area image coverage (not necessarily at visible wavelengths) at lower spatial resolution (a few km) is also required for long-term monitoring of larger regions. This capability is particularly important in detecting surface changes, some of which mark recent activity such as fresh impact craters. Once identified, high-resolution observations enable detailed study.

The goal of characterizing possible ground movement due to ice-related, thermal, or tectonic processes requires a method for measuring changes at the few-cm vertical scale in datasets collected over intervals of weeks to months, and preferably over large regions of interest. There were concerns raised regarding the likelihood of a detectable deformation event within the expected primary MSO mission, but the great importance of any such detection to the development and deployment of a surface network mission argues for making these measurements.

The current distribution of ice trapped in frozen ground at high latitudes is a major element in understanding the inventory and movement of water on Mars. The upper several meters of the Martian regolith at high latitudes is predicted to contain a significant amount of water ice. The presence of this ice was confirmed by observations of the upper ~1 m by the Gamma Ray Spectrometer (GRS) suite on Mars Odyssey. GRS observations indicate that ice volume fractions in the upper meter are over 50% in the polar regions, decreasing to 10% or less near 50-60° latitude. At mid-latitudes the ice is unstable near the surface and the hydrogen signal in GRS data can be explained by hydrated minerals, but ice may be present at greater depths.

The SAG-2 gave high priority to identification of thinly mantled "clean" ice deposits. Geologic features formed by the action of ice in frozen soil are common on Earth. Polygon patterned ground is the most ubiquitous of these features, resulting from seasonal thermal contraction and cracking in ice-rich soil. Polygons are observed in abundance in the Martian high latitudes, ranging in size from 1 to 100's of meters. Such features are an indication of current ice-rich soils or past ice history. The GRS data, however, are of low resolution (300–600 km), so the local-scale distribution of ground ice and expected relationship to patterned ground is yet to be confirmed. A search for shallow, relatively "clean", subsurface ice covering areas a few hundred meters or more in extent (frozen lakes, buried compact snow, or relic glacial ice), based on morphologic, density, electrical, or other diagnostic differences from ice-poor areas is needed.

6.3.4 Priority Measurements

The MSO measurements that address these investigations comprise (in priority order):

Surface Imaging. Based on interest in observing sedimentary layering and other geologic signatures of ancient climate, creating stereo topographic maps of targeted areas, searching for modern-day change due to ice, water, and aeolian processes, and to characterize landing site hazards, MSO should carry an imaging system with a spatial resolution of better than 1 meter (~ 30 cm / pixel scale) and >100:1 SNR as a minimum criterion, with strong scientific interest in higher resolution should a combination of increased payload mass or improved instrument technology permit. Current estimates of the mass and cost of a 5-10 cm resolution camera system led to a majority opinion that this option is not feasible for an MRO-class payload with several major elements intended to address multiple scientific themes. A wide-field camera, of low mass and cost, was also identified as being of high interest.

Shallow Subsurface Imaging. The sub-group advocates that MSO investigate the shallow subsurface of Mars to:

(a) Reveal geologic features associated with habitable settings and past environments.
(b) Identify and characterize recent impact features over large areas.
(c) Provide a detailed mapping of ground ice at high latitude as a feed-forward to subsurface drilling/sampling.
(d) Characterize volcanic and impact features to refine the global geologic history.
(e) Characterize near-surface rock abundance as a feed-forward to eventual drilling in high-priority targets.
(f) Search for evidence of ground movement due to volcanic or tectonic processes as a feed-forward to eventual surface network missions.
(g) Search for small-scale topographic changes associated with sublimation of subsurface ice.

This investigation can be accomplished by a synthetic aperture radar (SAR) imaging system with wavelength in the 20-30 cm range using the spacecraft high-gain antenna. Ground penetration of 3 m or more in Mars surface materials is required. Image spatial resolution of 25 m for at least targeted areas is required, with lower resolution of 75-100 m acceptable for synoptic observations. Surface change detection at the few-cm vertical scale is required.

Compositional Measurements. A few investigations developed by the sub-group point toward composition-related measurements in near-infrared and/or thermal IR wavelengths. There are two areas where advances in composition can be made from orbit: 1) Higher spatial resolution thermal infrared spectroscopy ~ 10-20m/pixel, to fully identify compositional diversity seen in THEMIS, but not resolvable by TES. In particular, recent discoveries of quartz and high-silica phases will not be addressable with CRISM. 2) Very high spatial resolution SWIR spectroscopy, roughly a few m/pixel, to do precise observations of locations identified with CRISM/OMEGA. This may direct precision landed operations to high priority aqueous mineralogy. There is also a strong desire on the part of the community to have landed SWIR spectroscopy to ground truth OMEGA and CRISM, though this was not considered by the SAG-2.

Table 6.3 Major Geology Themes and Goals:

Major MEPAG Goals	Science Themes	Observation Goals	Measurements Needed	Measurement Requirements	Potential Instruments
IA2. Geological History of Water on Mars	Ancient Environments	Characterize depositional settings of ancient sedimentary rocks exposed in outcrop form. Distinguish coarse- from fine-grained valley channel deposits.	Data to reveal bedding structures indicative of geologic setting. Information on the extent of potentially buried bedrock related to outcrops. Information on average size of transported rocks.	5–30 cm/pixel visible imaging; measurement of subsurface properties and near-surface rock abundance; high-resolution mapping of thermal inertia to constrain particle sizes of sub-resolution rocks.	Camera for surface features; Imaging radar for subsurface features and sub-pixel roughness; thermal-IR imager for thermal inertia.
		Determine climate-related or diagenetic-related mineralogies of specific layers or packages of layers exposed in sedimentary rock outcrops.	Direct correlation of mineral spectra to specific layers or packages of layers at few meters scale.	Capability to detect phyllosilicates, sulfates, carbonates, at spatial resolution scales of a few meters.	IR imaging spectrometer
IIB4. Physical records of past climate. IIIA2. Evaluate fluvial, subaqueous, and pyroclastic processes.		Identify landforms, such as fluvial channels, indicative of past climate and liquid water activity, beneath mantling sediment. Discriminate sedimentary from other processes across Mars.	Imaging that reveals geomorphology, including that beneath meters of mantling sediments.	3 m or more penetration. Required resolution range from 15-m to 100-m, depending upon scale of features. Increased coverage at 5-30 cm/pixel for exposed surfaces.	Imaging Radar, camera
IA1. Current Distribution of Water in All Forms	Dynamic Mars/Water on Mars Today	Characterize sites of possible recent water release and monitor for new water release.	Long-term high-resolution monitoring of likely sites for water release.	5–30 cm/pixel imaging, including stereo	Camera
		Determine the mineral species deposited by gully flows as a guide to formation mechanism and, if liquid-carved, habitability potential.	Spectroscopic identification of minerals left by possible surface water discharges.	Capability to detect solid and liquid water, evaporite minerals at spatial resolution at 1–4 m/pixel.	IR imaging spectrometer
		Understand the geologic history of gully regions and measure rates of change to constrain formation mechanism.	Characterize sequence of gullies beneath mantling sediment. Identify rate of change associated with gullies on regional to global basis. High-resolution topographic data needed for quantitative modeling.	1-3 m or more of penetration. 10-15 m resolution. Interferometric detection of change. Stereo for 1-m digital elevation models	Imaging radar and repeat-pass interferometry, camera

IIIA1. Present state, 3-d distribution, cycling of water and other volatiles.	Dynamic Mars/Ice on Mars Today	Observe and measure rate of polar landform change over a martian decade (or more) timescale. Need for monitoring through polar night.	South Polar Residual Cap: Images of at least 3 m/pixel to continue record of monitoring CO2 scarp retreat (and search for deposition sites, if they exist) started by MGS MOC. North Polar Residual Cap: Images of at least 30 cm/pixel to seek change in pits and other features formed in H2O ice observed by HiRISE. Both Caps: Detection and regional mapping of cm-scale changes in deposits, particularly the permanent caps, over days to years.	30–300 cm/pixel visible imaging; detection and mapping of cm-scale ground changes related to volatile migration during day and night; high-resolution monitoring of temperature over selected locations.	Camera for hi-res stereo visible photos (daytime, localized); Imaging radar repeat-pass interferometry (day/night, regional); themal-IR imaging
		Characterize the physical properties of the upper 10 m or more of the polar deposits, and link regional variations to outcrops imaged by visible/near-IR systems.	Characterize shallow physical properties changes due to dust loading or layering.	Penetration of 10 m or more of the caps; spatial resolution 15-100 m.	Imaging Radar
IA2. Geological History of Water on Mars.		Refine the link between low-resolution hydrogen measurements and near-surface geologic features.	Identify extent of patterned ground beneath mantling sediments. Search for diagnostic physical differences between ice-rich and ice-poor ground.	1-3 m or more of penetration. 15-25 m resolution.	Imaging Radar
	Dynamic Mars/Geologic Processes on Mars Today	Characterize the current impact rate, to improve (relative to present results from MGS MOC) the statistics which pin down the present-day impact cratering rate. Applications include age extimates for geologically-recent surfaces such as gullies and surfaces cut by gullies or partially covered by gully fans.	Search dust-covered regions (e.g., Tharsis, Amazonis, Elysium, Arabia) for new dark spots of several hundred meters to a few kilometers diameter. These dark spots are candidate fresh impact sites. Follow up the observation of new dark spots with high resolution imaging of at least 3 m/pixel scale.	Image dust-covered (and other) regions at least once per year with scale at of least 600 m/pixel. Follow up each candidate dark spot by imaging at high resolution.	Wide-angle imager (any wavelength); high-resolution camera.
IIA7. Tectonic history of Mars; IIA8 Heat sources for hydrothermal processes; IIB1 Dynamics of the Mars interior.	Dynamic Mars/Geologic Processes on Mars Today	Identify sites of active deformation or near-surface hydrothermal activity resulting from endogenic geologic processes. May guide future landed investigations.	Characterize surface movement at the sub-meter scale due to tectonism or volcanic processes. Search for anomalous temperatures as a function of season or time of day.	50-100 m resolution scale posting, 1-5 cm level of change detection, 10-m thermal imaging.	Interferometric radar repeat-pass imaging; thermal-IR imaging with several broad bandpasses
IIIA2. Sedimentary processes including the present; IIA1i. Lower atmosphere climate and processes		Long-term monitoring of dust sources, sinks, and atmospheric transport based on observations.	Daily global imaging in at least red and blue visible wavelength bands.	Minimum 7.5 km/pixel like MOC daily global images.	Wide angle camera
IIIA2. Sedimentary processes including the present; IIA1i. Lower atmosphere climate and processes		Long-term monitoring of eolian bedforms for movement, sand transport rates. Detection and general rates of movement across dune fields on Mars.	Images of dunes, ripples, and drifts imaged at better than ~30 m/pixel by previous spacecraft. Concurrent need for large-area characterization of surface change.	Visible image resolution 5-30 cm/pixel. Detection of cm-scale movement on features.	Camera (localized) and interferometric repeat-pass radar (regional) imaging.

6.4 *Geophysics: Landed and Interior Science*

6.4.1 Background

6.4.1.1 Importance of Interior Investigations for Mars Science

It is no accident that the investigation of the interior of Mars has been high on the priority list of every NRC planetary science strategy document since the first COMPLEX report in 1977. Knowledge of the composition, structure, and history of Mars is fundamental to understanding the formation and evolution of terrestrial planets in general, and provides insight into the history and processes of our own planet. Thus there are compelling scientific motivations for the study of the interior of the planet in its own right. In addition, the study of the interior provides important clues about a wide range of topics, including the early history and geologic evolution, formation and loss of the atmosphere, geothermal energy and habitability.

Understanding of the interior of Mars is fundamental to the interpretation of the surface record. Interior processes are the ultimate driver for both volcanic and tectonic activity. The delineation of the elementary interior structure (core, mantle, crust) and the establishment of basic thermal boundary conditions for the planet's thermal history are essential components to understanding Mars and its history.

The last 20 years has seen great progress in the modeling of heat transfer through planetary mantles. The growing capabilities of computers have allowed numerical studies to take into account more and more of the complexities of the rocks. The main discovery has been the characterization of the so-called 'conductive lid' regime: the convective domain is located beneath a thick lithosphere through which heat is transferred by conduction. Applied to Mars, this model provides three main results: 1) The conductive lid is about 200 km thick; 2) The mantle temperature just beneath the lid is close to melting point; and 3) The core is still liquid.

The velocity of seismic waves traveling through the mantle would provide information on the thickness of the conductive lid, on the presence of a partially melted mantle, on the temperature of the mantle and on the state of the core. Such measurements would provide constraints on the thermal evolution of planet Mars. But they would also bring new constraints on the modeling of the thermal evolution of terrestrial planets. By comparing Mars and the Earth, new ideas will emerge on the relationship between convection and plate tectonics.

Delineating the structure and dynamical processes of the deep interior is fundamental for understanding the origin and evolution of Mars in general, and its surface evolution and the release of water and atmospheric gases in particular. For example, the thickness of the crust and the size and composition of the core provide strong constraints on the bulk composition of the planet and the manner in which it differentiated. Knowledge of the physical and thermal evolution places constraints on the composition, quantity, and rate of release of volatiles (water and atmospheric gases) to the surface. Evidence that Mars had a magnetic field early in its history has important implications for its formation and early evolution, as well as for the retention of its early atmosphere.

The intense interest in the possibility of life on Mars provides additional emphasis for these investigations. The possible formation of habitable zones at or near the surface of Mars is tied inextricably to the origin and evolution of the planet as a whole. In particular, the bulk composition, differentiation, and thermal/chemical evolution of the interior governed the magnetic dynamo, provided the crustal foundation and basic chemical building blocks, and drove the volcanic and tectonic processes that have shaped the surface and the atmosphere-hydrosphere-cryosphere system through time. For example, the delivery of mantle-derived volatiles to the surface via volcanism is a key factor in the evolution of the atmosphere and water budget. The timing and character of the early dynamo may have played a crucial role in shielding the early atmosphere and surface, providing a conducive environment for pre-biotic chemistry. Regional variations in the subsurface thermal environment may modulate the locations and timing of habitable zone development and evolution.

Thus understanding the interior and atmosphere contributes directly to understanding the habitability of Mars, primarily in the past, but also in the present in terms of such things as the oxidation state of the mantle (relating directly to possible non-biogenic origins of atmospheric methane) and the availability of geothermal energy for sustaining biotic processes at depth. And in a fundamental sense, the interior processes that resulted in the present planet must be understood in order to be able to separate their geochemical patterns from possible subtle chemical biosignatures. Any putative direct detection of life (e.g., ALH84001) or lack thereof (e.g., Viking) without a broader understanding of the system in which that life must exist and with which it must intimately interact will be fraught with uncertainty.

However, despite these arguments, the interior of Mars remains largely unexplored with critical gaps in our understanding of how Mars evolved as a planet.

6.4.1.2 Single Station vs. Network Measurements

The most effective method for probing the deep interior of Mars is with a widely distributed network of at least four landers carrying seismometers, heat flow probes, magnetometers and precision tracking systems. Such an ambitious mission has been repeatedly recommended by the NRC, and is being considered for a future launch opportunity by the Mars Exploration Program. But given that measurements constraining the structure and processes of the deep interior are virtually nonexistent, any information that a single station could obtain would result in a significant leap in our understanding of the interior structure. It would also provide a strong foundation for more effectively planning for a future network.

Seismology. A network configuration is particularly valuable for seismic investigations. It provides wide geographic coverage allows for the straightforward use of body wave arrival times at multiple locations to identify and locate seismic events in space and time, and to derive seismic velocity structure. Arrival times are the most straightforward measurements that can be made on seismic records, and this is the method by which most of the information on the interior structure of the Earth and Moon has been acquired. In addition, the redundancy and spatial coverage (allowing proximity to more potentially seismogenic regions) provides significant robustness to a seismic experiment that will not be available to a single station. However a seismic signal is extremely rich in information content, and there are numerous methods by which the characteristics of its source and path can be derived. Many of these can be effectively applied to the measurements from a single seismic station, and will be described in the following section.

Heat Flow. There are several reasons for which a distributed collection of heat flow measurements are desired. First, heat flow from the interior is not expected to be spatially uniform across the surface of Mars. Variations in regional volcanic activity or the distribution of radiogenic elements in the crust can cause significant differences in heat flow. Also, deriving the heat flux from the interior requires that its temperature gradient be separated from other signals due to diurnal, seasonal and climatic variations in the surface temperature. The first two of these can be overcome by measuring temperature to a few meters depth. But the climatic variation expected from changes in the obliquity extends beyond the depths, which are likely to be achieved in the foreseeable future. Fortunately, this signal has a latitudinal variation that, if sampled, can be used to identify and correct for it.

Thus multiple measurements will eventually be required to accurately characterize the mean heat flow of Mars. But these measurements do not have to be taken simultaneously; such a collection can be accumulated over many years. A single measurement will constitute a valuable first step toward this objective, and will provide our initial insight into the thermal state of the interior.

Precision Tracking. A network would enormously increase the value of surface tracking measurements over that of a single lander. Previous tracking of Viking and Pathfinder spacecraft on the surface of Mars has resulted in a significant improvement in our knowledge of the moment of inertia (and thus the size and composition of the core) by measuring the precession. Another station with a dedicated radio science experiment would result in an order of magnitude improvement in this parameter due to advances in radiometric measurement capability and an extension of the time series initiated during the Viking mission. Simultaneously tracking multiple locations on the surface would further improve the accuracy of this measurement. If multiple latitudes were accessible, it would allow for a direct measurement of the polar motion, adding nutation and polar motion (e.g., Chandler Wobble) to our arsenal of interior constraints, further refining estimates of core parameters (liquid vs. solid, presence or absence of an inner core) and mantle inelasticity (related to thermal state). It should be emphasized, however, that valuable measurements can be made from a single lander that will greatly increase our knowledge of interior structure.

Preparing for Future Missions.

With the failure of the Viking seismic experiment to return data on the seismic characteristics of Mars, future seismic networks missions are faced with the difficult task of preparing for the widest range of possible situations. Not only is the rate and spatial distribution of seismicity only estimated from first principles, but the level, spectral character, and temporal variability of seismic background noise is completely unknown. Similarly, the character of Martian seismic events as manifested in seismograms can only be guessed at by analogy to the Earth and Moon. The lunar experience provides a cautionary tale, in that the many seismic events recorded by the Apollo 11 seismometer were not recognized as such until a known event (the crash of Apollo flight hardware) revealed that much of what had been interpreted as noise were actually moonquakes with unanticipated and dramatically un-Earthlike characteristics. With no a priori knowledge, it is necessary to maximize all the measurement parameters (e.g., sensitivity, bandpass, number of stations, etc.) in order to assure the success of the mission. Measurements from a single "pathfinder" seismometer, with sufficient sensitivity and observation time, could prove valuable in relaxing requirements and simplifying the design for a future full network mission.

6.4.2 Priority Goals and Measurements

The first-order objectives of a geophysical lander are to determine the seismicity (seismic activity and distribution; impact frequency), and provide information on crustal thickness and structure; core size, density and state (liquid or solid); seismic structure of the mantle; and thermal state of the interior.

6.4.2.1 Seismic Activity and Impact Frequency

One of the greatest uncertainties in using a single station to provide bounds on interior structure is whether a sufficient number of quakes will be detected of sufficient magnitude to provide useful results. The lack of detection by the Viking seismic experiment (which was woefully insensitive) is consistent with an upper estimate of the Martian activity comparable to the Earth's intraplate activity. Theoretical estimates from thermoelastic cooling and surface faults predict a level of activity within this bound but still ~100× greater than the shallow moonquake activity detected on the Moon. This level would provide ~10-50 quakes of seismic moment $\geq 10^{15}$ Nm (roughly equivalent to terrestrial magnitude m_b=4) per year (throughout Section 6.3 we will use the term "year" to refer to an Earth year, roughly one-half Mars year). Quakes of this size should be globally detectable by a seismometer with a sensitivity of 10^{-9}m/s^2 or better. Many more smaller quakes (from terrestrial and lunar experience there should be ~25× more quakes for each unit decrease in moment magnitude) will be detectable if the station is located relatively nearby (within few thousand km).

Distribution of seismicity can be determined by monitoring the body wave frequency band (~0.1-2.5 Hz) for seismic events. The approximate epicentral distance can be derived from the differential P-S travel time on the vertical record. The error in epicentral distance will be ~10% (roughly the differences among a-priori of Mars seismic models), which will improve as interior models are refined. The azimuth can be measured using the horizontal components, yielding an error of ~15% in azimuth.

Thus given enough measurement time (at least an Earth year, to account for the large uncertainties in current estimates), a single sensitive seismometer should be able to determine the seismic activity of Mars. The level of seismicity gives a measure of the current level of tectonic (and perhaps volcanic) activity, both in terms of intensity and geographic distribution. Current estimates of seismicity depend on theoretical thermal cooling calculations or extrapolation of historical faulting. Thus the measurement of seismicity, regardless of the actual number of events detected, will provide fundamental information about the dynamics of Mars, providing insight into current levels of tectonic deformation.

The unique characteristics of impact seismograms allow them to be differentiated from endogenic events. These seismograms can thus provide a direct measure of the current rate of impacts, along with an estimate of their sizes. Hundreds of impacts per year were seen on the Moon, but the environment of Mars is very different. Asteroids strike Mars at an average velocity of 10 km/s rather than 20 km/s at the Moon, so impact energy is reduced by about a factor of four. The thin Mars atmosphere is able to disrupt weak bolides and decelerate small objects. Regolith is generally thinner or indurated on Mars compared with the Moon, but aeolian mantles are common. There are far fewer craters smaller than 10 m diameter on Mars compared with the Moon, except in secondary fields. Most of the small objects (mostly asteroids rather than comets) that do impact the surface make shallow craters and clusters of craters, indicating that these impacts are due to clusters of objects rather than intact rocks. Malin et al. (2006 Science) reported 20 "new" or darkened spots that correspond to fresh impact craters over 1/6 of the Martian surface in the MGS era (~5 years average time span for observation of changes). HiRISE images indicate that about half of the impacts have experienced aeolian modifications and may be older than the MGS era. Based on these results we should expect ~10 to 20 impacts per year of sufficient magnitude to create 10 m or larger craters, likely detectable as seismic events. Several of these MGS-era impacts are associated with concentrations of dust avalanches, perhaps triggered by seismic shaking. Note that the approximate locations of such events can be used to target orbital imaging to look for the resulting new craters on the surface. The combination of an impact seismogram with an image-based impact location provides a powerful tool (comparable to the Saturn IVB lunar impact) for probing the crust.

6.4.2.2 Crustal Structure

Several independent methods can be used to determine crustal structure. The receiver method (using body wave mode conversions at the base of the crust) has been successfully applied to the Moon. This method has the advantage of not requiring larger quakes that are necessary to produce surface waves and normal modes. A second approach would be to use natural impacts as described in the previous section. This method would be analogous to the Saturn IVB impact experiment on the Moon, which produced the best Apollo-era estimates for lunar crustal thickness.

Another method uses the group velocity dispersion of surface waves at lower frequencies (10-100 mHz) from the records of relatively large events. Such dispersion curves are very sensitive to the crustal thickness, and well-developed surface wave trains can be used to model the large-scale vertical structure of the crust (and the uppermost mantle). The drawback of this method is that surface waves are not generated on Earth for quakes smaller than magnitude ~5. Thus this method would require the detection of relatively rare events, although several would be expect within a year of observation if current activity estimates hold.

6.4.2.3 Mantle Structure

For a single seismometer, the most effective techniques for studying deep structure utilize normal mode frequencies, which do not require knowledge of the source location. Normal mode peaks from 5-20 mHz (the frequency range sensitive to mantle structure) can be identified for a detection noise level of 10^{-9}m/s^{2}/Hz$^{1/2}$, and these spectral peaks can be inverted to derive the radial structure of the mantle. This structure is particulars sensitive to compositional stratification or polymorphic phase transitions. A useful analysis can be accomplished by using single record of a large quake of moment $\geq 10^{18}$Nm (equivalent m_b~6) or by stacking quakes with an equivalent cumulative moment. Again, this requires relatively rare, but reasonably expectable events.

6.4.2.4 Core Structure

Precision tracking of a single station, using an X-band direct-to-Earth carrier (or dual frequency tracking, X-band and UHF, through an orbital relay asset) can be used to infer interior structure from its effect on variations in the orientation of Mars with respect to inertial space. The precession, nutation, and polar motion of Mars result from the interaction of the interior mass distribution with the gravity of the Sun. Analyses indicate projected improvements over Viking and Pathfinder of a factor of 10 in precession, resulting from the increased total time span since Viking and a longer contiguous time span (1 Mars year vs. 90 sols for MPF) and better data accuracy (particularly with respect to Viking). This would provide a considerable (better than a factor of 5) improvement in the estimate of the size of the core and its density.

A capable very-long-period seismometer may also be able to contribute to the determination of core size through the measurement of the Phobos solid tide amplitude. Detailed modeling has shown that for a seismometer of the sensitivity discussed above (at the Phobos orbital period, 7.65 hours) this measurement is limited by the temperature noise. But because of the periodic and continuous nature of the signal, long-term stacking can be employed and a year-long time series should yield a scientifically useful core signature.

6.4.2.5 Thermal State

Surface heat flux (heat flow) can be measured by determining the subsurface temperature gradient with a string of thermistors distributed at depth, along with a corresponding thermal conductivity determination (typically derived from heat pulse decay observations). These measurements must extend down at least three meters in order to sample below the annual thermal wave. The main difficulty is penetrating to depths ≥3 m using a relatively modest resources of a lander. Whereas drilling to these depths is still complex and expensive, recent developments of self-hammering penetrators (such as that flown on Beagle-2) show promise for being able to relatively inexpensively deploy thermal strings at depths up to 5 meters.

In addition to observing the thermal boundary, it is possible to obtain information on the temperature profile of the deep interior using electromagnetic sounding methods. The most mature of these methods (applied to the Moon during the Apollo missions) uses a magnetometer on a surface station to measure the magnetic response of the planet to an external time-varying field (in this case supplied by Mars' ionosphere) as a function of frequency. From this information, one can obtain the resistivity profile, which can be interpreted in terms of rock temperature, to depths of thousands of kilometers. However this method requires independent knowledge of the inducing field, either from simultaneous orbital magnetic measurements or by measuring the low-frequency electric field vector at the surface station itself.

Table 6.4 Geophysics: Landed and Interiors Goals Matrix - Single Station Assumed

MEPAG Objective Addressed	Science Question	Measurements Needed	Potential Instrumentation	Justification
MEPAG III.B. Investigate the internal dynamics and structure of Mars to better understand its formation, differentiation, and subsequent thermal and geological evolution.	What is the structure of the Martian crust (thickness, density/composition, large-scale layering? (MEPAG III.A.6, III.B.1, III.B.3)	Seismic body wave signals (0.1-10 Hz) from regional marsquakes and impacts (search for crustal reflections/ refractions; determine receiver function).	Highly sensitive (better than 10^{-8}m/sec^{2}) very-broad-band (0.1 mHz – 10 Hz) 3-axis seismometer.	Measurements pertaining to the structure and processes of the deep interior of Mars are virtually nonexistent. These measurements will define the crustal thickness, mantle structure, and core size, density and state, providing essential constraints on the formation and evolution of Mars.
		Seismic surface wave signals (10-100 mHz) from moderate-size ($m_b \geq 4$) marsquakes (interpret group velocity dispersion).		
	What is the structure of the Martian mantle (density/ composition, stratification)? (MEPAG, III.B.1, III.B.3)	Seismic normal mode signals (5-20 mHz) from large-size ($m_b \geq 5$) marsquakes (identify normal mode frequency peaks).		
	What is the size, composition and state of the Martian core? (MEPAG III.B.1, III.B.2, III.B.3)	Phobos solid tide amplitude at 0.37 mHz (determine tidal Love number from long-term stacking of tidal signal).		
		Accurate determination of the planetary rotation vector direction and amplitude (determine rotational parameters such as precession, LOD variations, nutation).	High-precision dual-frequency radio tracking at the decimeter level.	
	What is the thermal state of the interior? (MEPAG III.B.3)	Thermal profile to a depth of at least 3 m, along with thermal conductivity (determine heat flux from the interior).	Series of thermistors distributed down a 3-m (or deeper) borehole capable of resolving thermal gradients to ~10^{-3}K/m.	Heat flow and the interior thermal structure provide fundamental information on the distribution of radiogenic elements and on the thermal history of the planet, and provides crucial constraints on differentiation processes, subsequent magmatism, and the history of the magnetic field.
		Electromagnetic sounding of the deep interior using ionospheric disturbances (determine the thermal profile from electrical conductivity).	Surface magnetometer in conjunction with orbital magnetic measurements.	
MEPAG III.A.7: Document the tectonic history of the Martian crust, including present activity.	What is the current level of tectonic/volcanic activity on Mars?	Observations of the distribution (with time, location, size) of marsquakes (distance obtained from P-S interval or emergence angle; direction obtained from P-wave azimuth; size obtained from distance-corrected amplitude).	Highly sensitive (better than 10^{-8}m/sec^{2}) short-period (0.5-20 Hz) 3-axis seismometer.	Seismicity provides a measure of the vigor of current tectonic activity and places constraints on the thermal and tectonic history of Mars. These measurements will provide fundamental guidance for the design for a full geophysical network mission in terms of the frequency and spatial distribution of seismic events and the characteristics of both seismic signals and noise..
MEPAG III.A.3: Calibrate the cratering record and absolute ages for Mars	What is the current population of impactors at Mars' orbit?	Observations of the distribution (with time, location, size) of impact events (distance obtained from P-S interval or emergence angle; direction obtained from P-wave azimuth; size obtained from distance-corrected amplitude).		Observing the current impact rate will help to anchor the crater size-frequency curves, allowing comparisons of the population with that of the Earth-Moon system.

7 Strawman Instruments

Overall, the SAG-2 members were opposed to being overly specific with regard to instruments that would make the observation and measurement goals described in the previous section. In an effort to constrain mission implementation and resource liens, strawman instruments were put forth by each group. These instruments are proposed as an "existence proof" to achieve science objectives described in section 6. It is recognized that other instruments may be able to achieve the measurement and science goals previously identified and the higher-level goals should be referred to in order to achieve the broadest possible creative contribution from the science community at large.

The instruments are briefly summarized below, more or less in order of atmospheric, polar, geology and geophysics, though several instruments support goals and objectives in multiple groups. If there were higher priorities among the submitted instruments these are noted.

Cost and mass estimates were made by the SAG-2 members with familiarity with such instrumentation and were checked against values for similar instrumentation carried by the MSO project office. As an additional reality check, the MRO payload was made from our equivalent strawman instruments and was found to be consistent. Specific heritage is noted below and cost and mass estimates are provided in the mission scenario table in Section 8. Cost estimates do not include Phase E costs or reserves as these are carried separately. We did not consider the cost of either the lander delivery system or the orbiter accommodation for a lander in our scenarios. Specific mission liens such as orbital altitude and inclination, spacecraft roll and stability are addressed for each instrument. Data rate was suggested to be equivalent to MRO, or ~ 50Gb/day, particularly if multiple imaging instruments are involved.

7.1 *Solar occultation FTIR*

A solar occultation Fourier-transform infrared spectrometer with spectral resolution ~0.02 cm^{-1} over 850-4300 cm^{-1} has sufficient signal-to-noise and spectral discrimination to achieve the parts per trillion detection sensitivity for the suite of target signature gases. Solar occultation, with its intense source, provides the ability to achieve simultaneous measurements of the vertical distribution of multiple chemical species from the surface to 100 km, including in moderately dusty conditions. Such devices have been used to characterize important trace constituents in the Earth's upper atmosphere (e.g., MATMOS, ACE). For solar occultations, the global coverage is controlled by the inclination of the spacecraft orbit. As the inclination increases more poleward of 74°, frequency of sampling, particularly at low and mid-latitudes, is compromised. The minimum mission requirement is to observe most latitudes at least once per Mars season and orbit trades were studied by the project and are discussed in more detail in Section 9.This instrument would need a large passive radiator or active cooling. Active cooling may add substantially to the cost and mass estimated in Table 8.

7.2 *Sub-millimeter spectrometer*

A submillimeter spectrometer observing in a wavelength range near 600 GHz, with a viewing geometry varying between nadir and limb views, can profile specific atmospheric trace signature species (including water) and temperature on a global scale with high horizontal resolution. (Not all trace molecules could be observed in this mode.). In this operating wavelength range, observations are unaffected by the presence of dust; species and temperature measurements can be acquired within the depths of the densest dust storms, allowing specifically the investigation of the potential influence of heterogeneous chemistry, including processes related to dust electrification. The submillimeter spectrometer in its limb-observing mode, through measurement of the Doppler shift of spectral features, can measure the wind velocity along the line of sight. This new element is important both for understanding the atmospheric circulation in general and in using inverse modeling to identify source regions for the signature gases as put forward by both atmospheric science and polar groups. No specific mission liens were identified.

7.3 *"MARCI-like" Camera*

A wide-field visible imaging system provides additional information on the global distribution of atmospheric dust and ices and global surveys of surface albedo changes. This instrument continues MGS/MRO atmosphere/surface monitoring and provides global dust distribution. It supports multiple objectives in atmospheric, geologic and polar processes. The MOC wide-angle mode and MARCI cameras are similar to what is envisioned for this instrument.

7.4 *Thermal IR or "Lite" spectrometer system*

This instrument can address multiple objectives or goals, depending on final design and configuration. An instrument of this class, similar to MGS-TES or MRO-MCS was envisioned to provide the daily global measurements of atmospheric dust and ices for correlation with species and temperature measurements from the submillimeter spectrometer under atmospheric state goals. It would provide input for model simulations by constraining the solar heating driving the circulation related to energy balance or dust/volatile exchange in measurements of climate and polar processes. A system with improved spatial and spectral resolution above that of TES can provide detailed mineral mapping of diversity seen in THEMIS data, in support of geology goals. Spatial resolution of 10 to 20 m at spectral resolution better than TES is achievable with modern technology and cooled systems.

7.5 *"HiRISE" Class Imager (HCI)*

A high resolution (sub-m/pixel), high signal-to-noise camera system of capability and mass similar to the MRO HiRISE instrument was considered a high priority by all three, but especially the polar and geology, groups. HiRISE provides images at 30 cm/pixel scale over a 6-km wide swath from 300 km altitude, and with at least 100:1 SNR. HiRISE on MRO can cover ~0.2% of the Martian surface at full resolution per Earth year in the mapping orbit. The utility of a comparable instrument on MSO is in additional coverage beyond that attainable with MRO, continued and longer-term monitoring of active processes, and the opportunity to image at different illumination angles. HiRISE-class imaging is widely considered by the engineering and landing site community to be the minimum capability required to support future landing site surveys. This camera system must permit viewing geometries commensurate with stereo mapping at high vertical and horizontal resolution over targeted areas. For polar processes a minimum orbital inclination was found to be 85 degrees in order to clearly observe most of the residual ice caps of both poles as well as observe detailed changes in the south residual CO_2 ice cap. Arguments were made to support a drifting local time of day, in particular the ability to re-image sites over a wide variety of illumination angles, which enables significantly greater information and understanding of small-scale features. Based on the HiRISE experience off-nadir pointing of the spacecraft needs to be allowed up to 30 degrees cross-track and spacecraft pointing stability of ~2 microradians (3 sigma) over 10 ms is required. Cost and mass was estimated based on HiRISE. Significant improvements to the focal-plane system may be possible if a few extra kg are available. It would also be possible to design a focal-plane system that tolerates poorer pointing stability while maintaining image quality.

7.6 *Multibeam Lidar Altimeter + Ultra Stable Oscillator*

In order to address multiple objectives related to polar mass and density of the seasonal cap, polar night energy budgets, cloud motions and atmospheric dynamics, the polar splinter group proposed a high vertical precision multi-beam lidar altimeter. The proposed Multibeam Lidar Altimeter is assumed to be similar to LOLA, scheduled for flight on the 2008 Lunar Reconnaissance Orbiter and aspects of the system are inherited from the successful CALIPSO lidar, which is presently operating effectively in low Earth orbit. Its vertical ranging precision is on the order of centimeters, an order of magnitude better than MGS/MOLA. New laser transmitter technology has longer lifetime and greater number of pulses, so that contiguous-footprint samples approximately 15-20m along-track can be produced, as part of an array of parallel beams as widely separated as kilometers to facilitate rapid sampling and densification of surface altimeter cross-overs. A three to five beam lidar altimeter that employs waveform-based echo recovery to further refine its ability to resolve cm-scale ranges and to quantify the within-footprint vertical structure (as roughness) and reflectivity (at the laser wavelength of 1064nm) is now achievable, with the additional capability of being able to resolve optically-dense atmospheric phenomena (i.e., clouds, hazes, hoods) at vertical scales as fine as 150m and along track at kilometer scales, from the top of the atmosphere to the surface. Such an instrument would significantly constrain the seasonal mass budgets, and it would do so with spatially resolved measurements with a factor of 20 increase in sampling density and 10 times higher vertical precision. This instrument could also produce a global, seamless digital elevation model (DEM) for Mars at better than 100m horizontal grid scale, with 3-10cm (RMS) vertical accuracy, and a related map of 100m scale vertical roughness with sensitivity to vertical structure at the 10cm level. Such products would support investigations in the Geology and Atmospheric Signatures and State theme areas, and also support autonomous precision landing solutions for eventual human exploration. In order to determine atmospheric mass in exchange with the surface an Ultra Stable Oscillator (USO) and radio science experiment to concurrently constrain atmospheric pressure must also be included (ideally employing the X-band mode of the MSO telecom system). Orbital inclination for optimized polar cap sampling should be between 85 degrees and 92.8 degrees. Inclinations below 82 degrees will degrade the ranging precision for the polar regions, but would still allow for sampling.

7.7 *Multi-spectral SWIR/TIR or "Capable" Spectrometer*

This instrument can fulfill varying objectives depending on how the instrument is configured. As envisioned by the polar group this instrument would combine both reflected solar and emitted thermal wavelengths, similar to the terrestrial ASTER instrument. The instrument would have approximately 30 SWIR channels at critical wavelengths for diagnostic ice and mineral spectral features and spatial resolution of roughly 100m. The TIR would have roughly

10 channels, plus optical and thermal bolometers at spatial resolutions equivalent to TES. Spatial coverage should be broad enough to allow frequent observation of seasonal and annual surface processes that are highly variable in space and time. This would allow high time resolution of seasonal processes and selected channels can clearly separate water, carbon dioxide, and dust while concurrently monitoring optical and thermal energy balance (via bolometers) for atmospheric transport and exchange. The goal is to quantify composition, dust content and variability, in addition to mass fluxes, supporting the altimetry measurement. An alternate view of this component is that is can represent a more capable high spectral resolution spectrometer system with higher spatial resolution to follow up on either CRISM or THEMIS discoveries. Heritage from the terrestrial community include Artemis, designed for military target identification from Earth orbit. These systems will probably require both passive and active cooling.

7.8 *1-m resolution camera*

The SAG-2 considers the equivalent of HiRISE spatial resolution as the minimum required for multiple science goals for imaging systems. In order to create mission scenarios that fit in the lowest POP cost guidelines a less capable imaging system needed to be included. This was proposed to be a MOC equivalent, or better than CTX, at roughly 1m/pixel and color capability is desired. Such an imager would have few advantages over a HiRISE class imager but it would be able to cover a greater area of Mars and provide better detection of changes if they are both resolved and understood at 1 m/pixel.

7.9 *Synthetic Aperture Radar*

A synthetic aperture radar (SAR) imaging system capable of penetrating 3 m or more of typical Mars surface material was suggested to reveal buried geologic features. This system must also be capable of measuring surface deformation at the few-cm scale through repeat-pass interferometry (InSAR). Published studies of Mars SAR applications show that a radar wavelength of 20-30 cm is appropriate for these investigations, based on conservative estimates of the near-surface loss tangent and expectations of achievable instrument signal-to-noise performance. One major accommodation issue for a SAR relates to the antenna, which must be carried as a separate 35-40 kg item unless the spacecraft high-gain antenna can be shared between telecom and radar imaging. The SAG-2 recommends that the dual-use option be facilitated in order to make a SAR feasible within the broad goals of MSO. An additional requirement is that the antenna must be at least 3m for optimal imaging resolution. A high-bandwidth SAR operated at nadir could provide additional information about the shallow, layered structure of the polar regions, with horizontal and vertical resolutions an order of magnitude improved over MRO's SHARAD. This SAR "mode" is of interest to the climate and polar processes theme-based goals of MSO. The technologies required for this type of instrument have been long demonstrated in both airborne (e.g., the NASA/JPL AIRSAR) and spaceborne systems (Magellan, Cassini SAR).

7.10 *Landed Geophysics*

A complement of three elements were envisioned to be the science baseline to justify a single drop off package (DOP). In priority order these are: landed seismology; precision tracking for geodetics; and heat flow/magnetics. This complement can meaningfully address the science goals outlined previously. We note that examples of all the instruments described in this section exist with TRL ≥ 6.

It is important to realize that a highly capable seismometer is necessary in order to justify the single-station experiment. As described in Table 6.4, there are specific requirements on sensitivity and frequency needed to obtain scientifically useful information relative to the science objectives. For example, a short-period seismometer (sensitive to frequencies > 0.1 Hz) can measure seismicity, impact flux, and may provide some constraints on crustal thickness, but will not contribute meaningful data on the deep structure of the planet. And given the uncertainty in the level of seismic activity, observing the seismic environment for significantly less than an Earth year may put even the basic determination of seismicity at risk.

A high level of precision tracking can be obtained by using a dual frequency system (e.g., UHF plus X-band) in order to cancel the path noise from variations in the ionosphere electron density. Thus the precision tracking experiment requires an additional X-Band transponder in addition to the basic UHF telecom system.

While the heat flow/magnetometer element was judged the lowest priority element of the lander payload, the SAG-2 included these instruments in the full desired science complement. The heat flow measurement is a difficult one, although ongoing development of self-penetrating “moles” show promise for making this measurement practical. A magnetometer is also at a lower science priority, although its low mass, power requirement and cost combine to make it an attractive addition.

It should be emphasized that the capabilities of the lander itself play an integral role in enabling these geophysical measurements. As a basic requirement, the lander must be able to deliver sufficient payload mass to the surface to allow instruments with the necessary capabilities. It must be able to support their minimum power and telemetry requirements. The seismometer and heat flow probe require direct access to the ground in order to properly make their measurements. For minimum science, the landed instruments need to operate for at least 0.5 of a Mars year and a full Mars year is highly desirable. Although there is room for compromise in all these areas, there are minimum levels beneath which the experiments will not be scientifically worthwhile.

7.11 *Landed Meteorology*

□The scientific objectives of the Atmospheric State landed science are achievable only with a highly integrated set of instruments. The integrated nature of the package is required because many of the observations only have full value when combined with each other. In addition to the instruments themselves, a boom is required to remove many of the observations from the disturbed conditions near the lander.

Pressure and temperature measurements can be obtained with instruments only slightly improved from those used on Pathfinder and Mars Polar Lander. Surface temperature and boundary layer atmospheric temperature profiles (and thus atmospheric back-radiation) can most simply be measured with a system similar to that being used on MSL REMS. This system is a set of thermopile detectors, each behind its own interference filter window, tuned to select either continuum thermal emission, dust, water or ice absorption features, or specific bandpasses in 15µm CO_2 band. The 3-D winds can be measured to the required precision and sampling frequency with a sonic anemometer. This instrument is also a fast-response thermometer, directly allowing the sonic anemometer to measure the eddy fluxes of both momentum and heat through the Martian boundary layer. A Tunable Diode Laser hygrometer (descended from those flown on Mars Polar Lander) can measure the water vapor present with sufficient accuracy and sampling frequency to meet the measurement requirements. When this is properly integrated with the sonic anemometer, these two observations can be combined to directly yield the water vapor flux. Finally, a vertical electric field sensor, sensitive across a broad range of field strengths can achieve the science goals outlined above concerning dust electrification. Such an instrument was developed for Mars03 MATADOR/ECHOS, and was tested terrestrially under similar conditions in the MATADOR field campaign.

8 Mission Scenarios

With strawman elements as defined in Section 7, the SAG-2 next considered how to combine various elements into mission scenarios that fit the core mission attributes (Section 3) with science synergies among the elements and potential for either follow up on existing program elements or feed-forward to future proposed missions such as AFL, Twin Mid-Rovers, a Long-Lived Network or MSR. In an open "brainstorming" phase, members of the SAG-2 suggested reasonable combinations and upwards of a dozen individual scenarios can be envisioned that combine elements to address broad goals of habitability, dynamics, or planetary evolution.

It became rapidly clear that because of the cost and mass limitations suggested for MSO not all high priority science objectives can be accommodated and significant orbital science will remain unaccomplished even after MSO. Given that no one mission scenario could be created with "something for everyone", the group sought to combine and refine scenarios that had the most desirable science elements addressing goals from two or more of the discipline (theme-based) splinter groups.

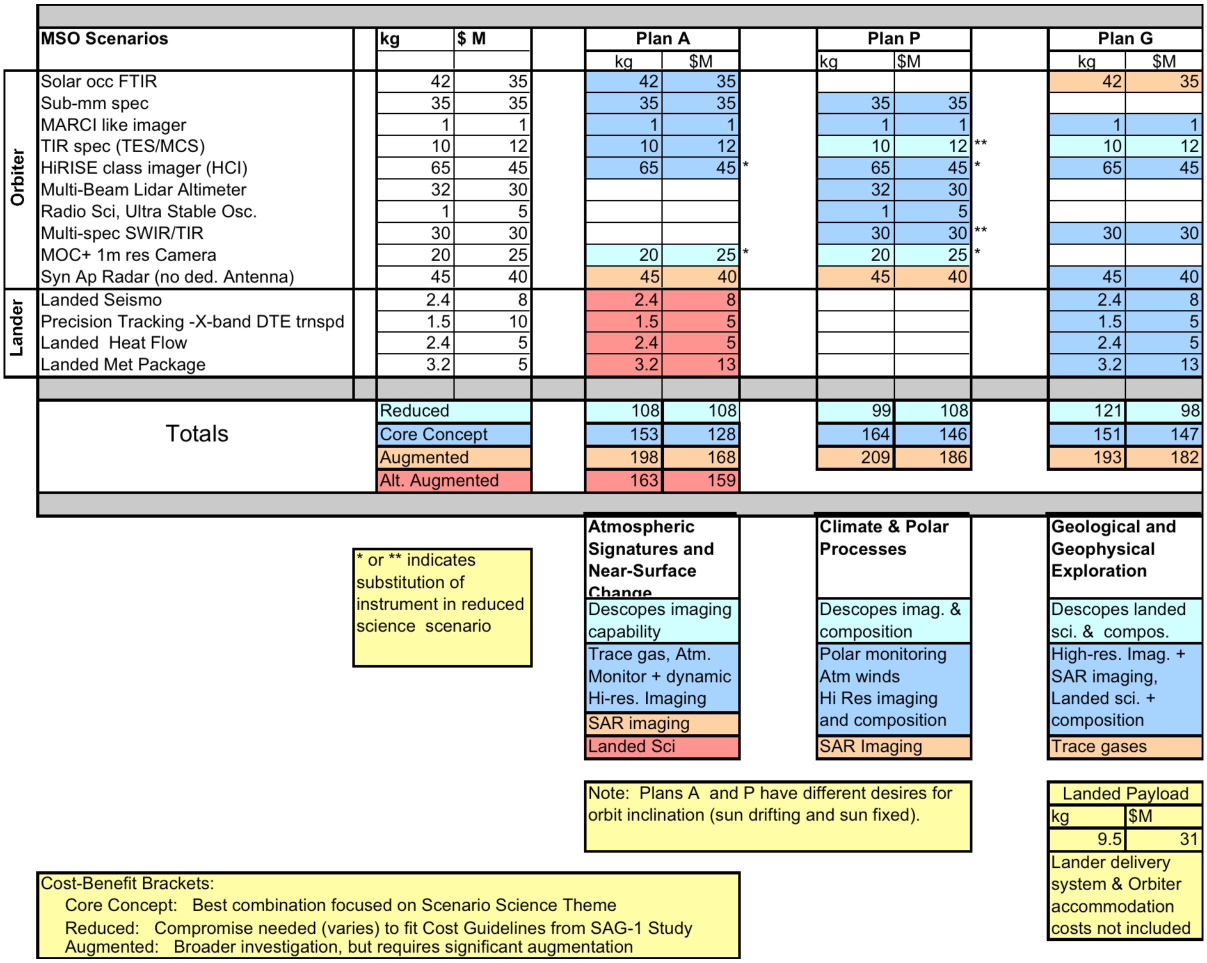
These possible combinations were grouped into three main categories: A Core Mission Concept (CMC), a "Reduced" example, and an "Augmented" version. "Reduced" and "Augmented" are with respect to the CMC. While these combinations are not the only ones that can be envisioned, the SAG-2 felt they represented the most reasonable trade space by retaining complementary science goals and exploring the range of cost guidelines as provided by the MSO Project and the NASA HQ Charter.

The Core Mission Concept was constructed to provide the best combination of instruments addressing the high-priority science goals within each science scenario while keeping key cross-disciplinary elements within reasonably constrained resources of mass and cost. The gain in science for the modest augmentation needed for the CMC was very high and it preserved the innovative, cross-disciplinary elements that are the hallmark of a core mission, as discussed in Section 3. In all three scenarios the Reduced case makes serious compromises with regard to measurement goals, to future mission support, or by supporting fewer cross-disciplinary elements.

These mission scenario plans (A, P, G) and the strawman instrument complements associated with each are shown in the following table. Here color and * or ** are used to denote instrument substitutions and descopes between the Core Mission Concept and the Reduced level, while color (orange, red) denotes alternate Augmented plans.

While augmented scenarios are outside the provided cost guidelines, these were in line with MRO flight system capabilities and allow the opportunity to pursue contributed elements for specific science objectives. In particular the SAG-2 is aware of Canadian, French, German and Italian instrumentation similar to many of our proposed strawman instruments and these contributions should be encouraged to achieve the most capable and interdisciplinary payload.

Table 8: Mission Scenarios



	MSO Scenarios	kg	$ M	Plan A kg	Plan A $M		Plan P kg	Plan P $M		Plan G kg	Plan G $M
Orbiter	Solar occ FTIR	42	35	42	35					42	35
	Sub-mm spec	35	35	35	35		35	35			
	MARCI like imager	1	1	1	1		1	1		1	1
	TIR spec (TES/MCS)	10	12	10	12		10	12	**	10	12
	HiRISE class imager (HCI)	65	45	65	45	*	65	45	*	65	45
	Multi-Beam Lidar Altimeter	32	30				32	30			
	Radio Sci, Ultra Stable Osc.	1	5				1	5			
	Multi-spec SWIR/TIR	30	30				30	30	**	30	30
	MOC+ 1m res Camera	20	25	20	25	*	20	25	*		
	Syn Ap Radar (no ded. Antenna)	45	40	45	40		45	40		45	40
Lander	Landed Seismo	2.4	8	2.4	8					2.4	8
	Precision Tracking -X-band DTE trnspd	1.5	10	1.5	5					1.5	5
	Landed Heat Flow	2.4	5	2.4	5					2.4	5
	Landed Met Package	3.2	5	3.2	13					3.2	13
	Totals	Reduced		108	108		99	108		121	98
		Core Concept		153	128		164	146		151	147
		Augmented		198	168		209	186		193	182
		Alt. Augmented		163	159						
				Atmospheric Signatures and Near-Surface Change			**Climate & Polar Processes**			**Geological and Geophysical Exploration**	
				Descopes imaging capability			Descopes imag. & composition			Descopes landed sci. & compos.	
				Trace gas, Atm. Monitor + dynamic Hi-res. Imaging			Polar monitoring Atm winds Hi Res imaging and composition			High-res. Imag. + SAR imaging, Landed sci. + composition	
				SAR imaging			SAR Imaging			Trace gases	
				Landed Sci							

* or ** indicates substitution of instrument in reduced science scenario

Note: Plans A and P have different desires for orbit inclination (sun drifting and sun fixed).

Landed Payload	
kg	$M
9.5	31

Lander delivery system & Orbiter accommodation costs not included

Cost-Benefit Brackets:
Core Concept: Best combination focused on Scenario Science Theme
Reduced: Compromise needed (varies) to fit Cost Guidelines from SAG-1 Study
Augmented: Broader investigation, but requires significant augmentation

8.1 *Plan A: Atmospheric Signatures and Near-Surface Change*

This plan follows up on recent discoveries of methane and active gullies (with implications for possible shallow subsurface liquid water) and fulfills the charter task to examine atmospheric trace gasses. The science return of the Core Mission Concept payload will fulfill all the key objectives of the Atmospheric Signatures and Atmospheric State (orbital science) investigations (6.1), many objectives of the Geology goals (6.3), and a few objectives identified under Polar Processes and Modern Climate (6.2).

Plan A payload elements will provide a comprehensive characterization of the chemical composition of the Martian atmosphere, its global distribution and variation with Martian season, with particular sensitivity for ultra-low abundance species that might be signatures of subsurface processes related to existing habitable zones and possible life. The payload elements will continue the record of global climate measurements of atmospheric temperature, dust, water vapor, and surface albedo and, in addition, provide new measurements that uniquely constrain and validate models of atmospheric dynamics and state, including direct measurements of winds. The submillimeter spectrometer, one element of the Plan A existence proof, will provide atmospheric state measurements under all atmospheric conditions. The simultaneous measurement of atmospheric state and composition enhances the capability to follow a detected atmospheric signature back to its surface source.

Provision of a HiRISE-class imager continues global observations capable of finding recent changes in surface features indicative of extant active processes and provides landing site imaging support for later missions, including exploration of zones of interest as defined by trace gas distributions.

Two augmentation options in particular have been identified. One augmentation option is the inclusion of a SAR to provide a new measurement approach for identifying topographic surface change and a new perspective for characterizing near-subsurface geological structure. This complements the atmospheric interest in active subsurface processes. The second augmentation option includes both a landed geophysics package and a landed meteorological station. The latter payload element is directly synergistic with orbital atmospheric science as described in §6.1.3.4 earlier in this report. Both the landed geophysics experiments and the Atmospheric Signatures payload elements potentially provide complementary evidence for extant volcanic processes.

In a “reduced” option, the Plan A payload has a 1-meter resolution camera instead of the HiRISE-like resolution imaging. This can continue global monitoring of surface change with reduced sensitivity and has reduced value for landing site imaging.

All versions of Plan A provide frequent, extensive measurements of atmospheric composition and state in polar regions that support an understanding of the seasonal exchange of volatiles between the polar caps and the effect that the seasonally-varying polar caps have on atmospheric conditions. In addition, detection of time-varying release of atmospheric signatures from polar regions is provided in all Plan A configurations.

The combination of trace gas measurements and surface imaging may provide uniquely useful guidance impacting on landing site selection particularly for AFL and MSR. The atmospheric state measurements alone will support future entry/descent/landing for any mission equator ward of ~74° and similarly for surface imaging feed forward to landing site selection. The augmentation in which the SAR is added to the payload can have feed forward for planning subsurface access. The augmentation in which the landed science element is a part of the payload provides an important precursor for a future landed network mission.

The primary mission constraint is the lower orbital inclination (74°) preferred by the solar occultation FTIR instrument to provide frequent measurements at each latitude to enhance detection of sub-seasonal variation in atmospheric signature surface sources. At this inclination, Atmospheric State measurements during two seasons can be acquired at least twice at different local times throughout the daily cycle, which will support identification of never previously characterized atmospheric phenomena that require separation from the seasonal signal to be understood. In addition, imaging of a common portion of the surface at different local times can enhance detection of sub-resolution objects as discussed earlier in this report. On the other hand, at this inclination, both optical and SAR imaging of the polar surface above latitudes of approximately 77° will be excluded. However, future landed missions most likely will target locations at lower latitudes, so this should not compromise the imaging required for most landing site surveys.

8.2 *Plan P: Polar and Climate Processes*

Plan P approaches the orbital imaging and geophysics elements of the charter through the lens of current polar processes and climate, addressing priority goals described in Polar (6.2), Geology (6.3) and Atmospheric State (6.1.2) sections. This scenario follows up on discoveries of active erosion of the residual south CO_2 ice cap and possible new results from the 2008 Phoenix polar lander which may increase the priority of landing in more polar regions for biological potential and climate studies. The residual north cap is the only surface reservoir of water and may be an important resource for future human exploration, and serves as the major source of water known on the planet.

Recent discoveries by MARSIS and SHARAD are showing that the polar layered deposits, once assumed to be sediments, are in fact largely dust-free water ice. Understanding how ice and soil-covered ice develop over time has implications both for short term and longer climate feedback mechanisms including both albedo and water availability. At the core of this lies a better understanding of the polar energy balance, both in annual and seasonal processes. Aside from landed polar science, the next highest priority observations recommended at the 4th International Mars polar conference were better constraints on the mass and energy budgets of the polar regions. In the Core Mission Concept, Plan P approaches the mass/energy balance through detailed monitoring of both poles in 4 dimensions, x,y,z,t using optical, near-infrared and thermal infrared imaging spectroscopy for albedo temperature and composition, multibeam laser altimetry for topography and mass exchange and high resolution imagery. Atmospheric winds and transport of dust and volatiles in and out of the polar region is supported by infrared and sub-mm spectroscopy, as well as via high-resolution atmospheric lidar. A global synoptic view and continuation of the decadal climate record is provided by a MARCI like imager. These instruments are also useful elsewhere on the planet for detailed topography and volume measurements, monitoring surface and atmospheric change and composition.

The augmented scenario includes near-surface imaging by means of high-bandwidth SAR to support identification of soil mantles over ice or layers in the interior of the residual ice sheets and PLD. An alternate scenario would include higher spatial resolution neutron spectroscopy. This latter scenario emerged very late in the process and the SAG-2 did not have sufficient time to consider it in detail as is further described in section 11.1.5.

The reduce scenario is restricted to the highest priority observations of the coupled surface/atmosphere exchange. The imaging capability is reduced and the compositional information is reduced to a simplified spectrometer for atmospheric temperature profiles, not the detailed composition and thermal mapping with season.

This scenario is expected to feed forward into the potential for polar landed missions (i.e., including possibly a polar AFL or one of the twin Mid-Rovers) or to provide a polar location constraint if a long-lived network (ML3N as per NRC Decadal Survey) should include at least one polar station. Imaging and SAR support landing site surveys and drilling potential at all locations on the planet. The multi-beam lidar would support development of a global DEM of the planet relevant to other themes and to future human exploration because of its high vertical accuracy and geodetic control.

To fully define the atmosphere-surface interactions, scenarios in which the preferred orbit drifts in local time of day were considered. Both a drifting local time of day and a fixed local mean solar time can work effectively in this scenario and should be studied in more detail by the follow-on SDT.

For climate and polar processes, orbital inclinations must support nadir polar measurements, so that inclinations from 85 deg to 92.8 deg are highly preferred. Inclinations below 85 degrees will severely limit the capacity to meet the Plan P objectives.

8.3 *Plan G: Geological and Geophysical Exploration*

Plan G satisfies three of the four specific requests of the MSO-2 Charter: (1) Science from a camera that would also support certification of future landing sites, (2) Orbital Geophysics, and (3) Landed geophysical package. It does not address the question of trace gasses, except in the augmented version. Plan G fully addresses both the Geology and Geophysics science goals described in Sections 6.3 and 6.4. Additional science from HiRISE-class imaging (HCI) would follow up on discoveries such as the present-day (last decade) impact events and debris flows associated with gullies. Continued long-term monitoring and detailed characterization of such events provides key constraints on understanding “Mars Today.” For orbital geophysics the SAR experiment is the major thrust, providing a first exploration of the uppermost few meters of regolith and mantling materials, and topographic change detection over broad regions. The landed package addresses interior structure objectives that have been a high priority for “next steps” in multiple MEPAG and NRC reports. The addition of capable spectroscopy for composition rounded out the high-priority surface science envisioned by the SAG-2. Continued climate monitoring is provided by a wide-angle imager as well as the SWIR/TIR experiment, and the landed package includes a meteorology station.

There is excellent scientific synergy among the elements of Plan G. For example, a seismometer might detect a new impact event and provide some information on its location, the wide-angle visible imaging and medium-angle thermal imaging can be acquired to find small changes in albedo or temperature, the HCI can verify if it was indeed an impact event and determine the number and dispersion of craters, and SAR can characterize the subsurface properties and topographic changes.

Atmospheric and polar sciences receive less emphasis in Plan G than in Plans A or P, respectively. The wide-angle imager and SWIR/TIR instruments and the landed met package do satisfy some of the atmospheric science goals, and provide support to future missions. The desire for a changing time of day provides unique atmospheric science opportunities compared to recent missions with similar payload assets. The changing time of day could be accomplished with an orbit that is nearly polar, such at 85º, so there would be excellent opportunities to observe the polar terrains with imaging, SAR, and SWIR/TIR, but Plan G lacks the Laser Altimeter. An 85º inclination orbit would also be useful for solar occultations via FTIR to search for trace gasses and to see if spatial and/or temporal variability exists. If such variability does exist, then the characterization possible in Plan G would be inferior to that of Plan A, given less complete seasonal coverage as a function of geography (function of orbit inclination) and lack of a sub-mm spectroscopy experiment for dynamics.

The reduced Plan G descopes the landed package and replaces the SWIR/TIR with a less capable TIR experiment while preserving the highest priority observations for geology, landing sites, and orbital geophysics. An alternate reduction would be to keep the landed package while eliminating or reducing orbital payload elements.

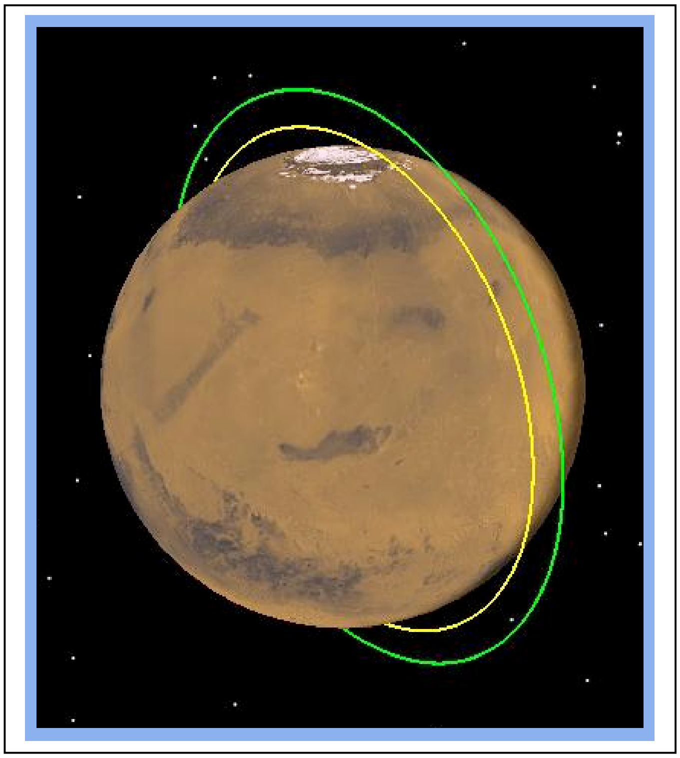
Plan G will provide significant feed forward to several possible future Mars exploration scenarios. The combination of HCI and SAR will provide excellent characterization of candidate landing sites for an Astrobiology Field Lab, mid-range rovers, Mars Sample Return, and potential human exploration. In addition the SAR provides subsurface information relevant to potential shallow drilling. The landed package could be a critical precursor for a network landed mission, providing a first station or baseline for a long-lived network or at least a proof of concept. In other words Plan G provides excellent support for all the future exploration pathways described in NASA's 2006 "Robotic Mars Exploration Strategy 2007-2016."

8.4 *International Cooperation*

There may be significant opportunities for international cooperation with MSO either through foreign instrument or instrument subsystem contributions or participation by international scientists as members of proposed instrument teams. Several space agencies are working on missions to Mars, including the 2013 ExoMars missions by the European Space Agency. Since the ExoMars mission may not be able to carry the entire payload that has been proposed by the different national agencies, there may be a possibility for those payloads to be embarked onboard a NASA mission if they fulfill the scientific requirements. The SAG-2 encourages that the AO be written in a way that invites such contributions to all candidate payload elements. Both instrument and team members contributed from international sources should be competed as part of the AO process, not simply "negotiated".

9 MSO Project Analysis

9.1 *Mission Design Summary*



Concurrent with the SAG-1 and the SAG-2 studies, a JPL group of mission design experts studied the trade space for the MSO mission, in order to gain a notional estimate of technical and resource requirements. Initial assumptions were that the spacecraft should be a MRO-class spacecraft, launched in 2013 and staying in Mars' orbit for about 10 years, with a mission cost similar to the MRO costs.

The mission is to carry a science payload, the nature of which is to be explored by the SAG-2 and a post – SAG-2 Science Definition Team. Further, MSO is to carry a capable telecommunications payload to replenish Mars' relay infrastructure as existing assets phase out, ensuring robust relay support for the 2nd decade of exploration. With its telecommunications capability, MSO will also provide critical events coverage, to monitor the arrival and landing of future spacecraft. To this end, fuel will be carried to provide several inclination changes (≈ 1˚ each) to slowly walk the orbit plane to the proper alignment each time. Approximately 60 m/s of delta-v is required for a 1˚ inclination change.

The mission design parameters are:

- Trajectory: Type II
- C3: 11.3 km/s2
- Launch: November 21, 2013
- Arrival: September 17, 2014

The mission scenario:

- MOI: 300 x 34,000 km orbit
- Inclination: 82.5˚ (TBD; see discussion in Mission Design trades below)
- Aerobrake: ≈ 6-9 months

The ten-year on orbit time would be divided into an approximately three-year "Science Emphasis" period (yellow orbit), and a seven-year "Telecom Relay Emphasis" period (green orbit). The science orbit would be at 300 km altitude (actually 270 x 330 km), and the relay period at 400 km (actually 370 x 430 km). The target launch vehicle is an Atlas V 4x1/5x1 series, with a 3,510 kg payload capability.

9.2 *Key Spacecraft Configuration Options*

Mission scenarios were considered by the MSO project that paralleled concurrent SAG-2 deliberations. The project selected plans that would bound the envelope of mass and cost from an early version of the mission scenarios provided by the SAG-2. Plans A and P were considered to be fiscally equivalent. The Project considered two cost levels. The nominal level of "OS" has a cost guideline of $100M and 160kg for science payload. This corresponds to the "Reduced" version of Table 8. A higher cost level "FSO+" has a cost guideline of $160M and 250kg for the science payload. This is consistent with the Core Mission Concepts and with some of the "Augmented" plans in Table 8. To demonstrate the effect of including a network lander (NL) to the mission, the MSO team added a lander element to its OS option. The accommodation of a landed payload was not done in detail, but only as an "existence proof" model. This analysis showed that MSO can accommodate 2-3 major science thrusts in addition to its telecommunications relay function. The spacecraft configuration was also notional. Detailed design requirements will follow a specific science theme. Table 9.2 describes spacecraft characteristic for the "OS" version. Subsequent columns reflect the change in technical parameters required to accommodate a more complex payload. For the "FSO+" payload, the entire spacecraft becomes more complex, primarily to accommodate both the HCI and the SAR. However, for the addition of a lander to the "OS" option, the impact on the spacecraft is mostly in the mass accommodation and increased I&T support.

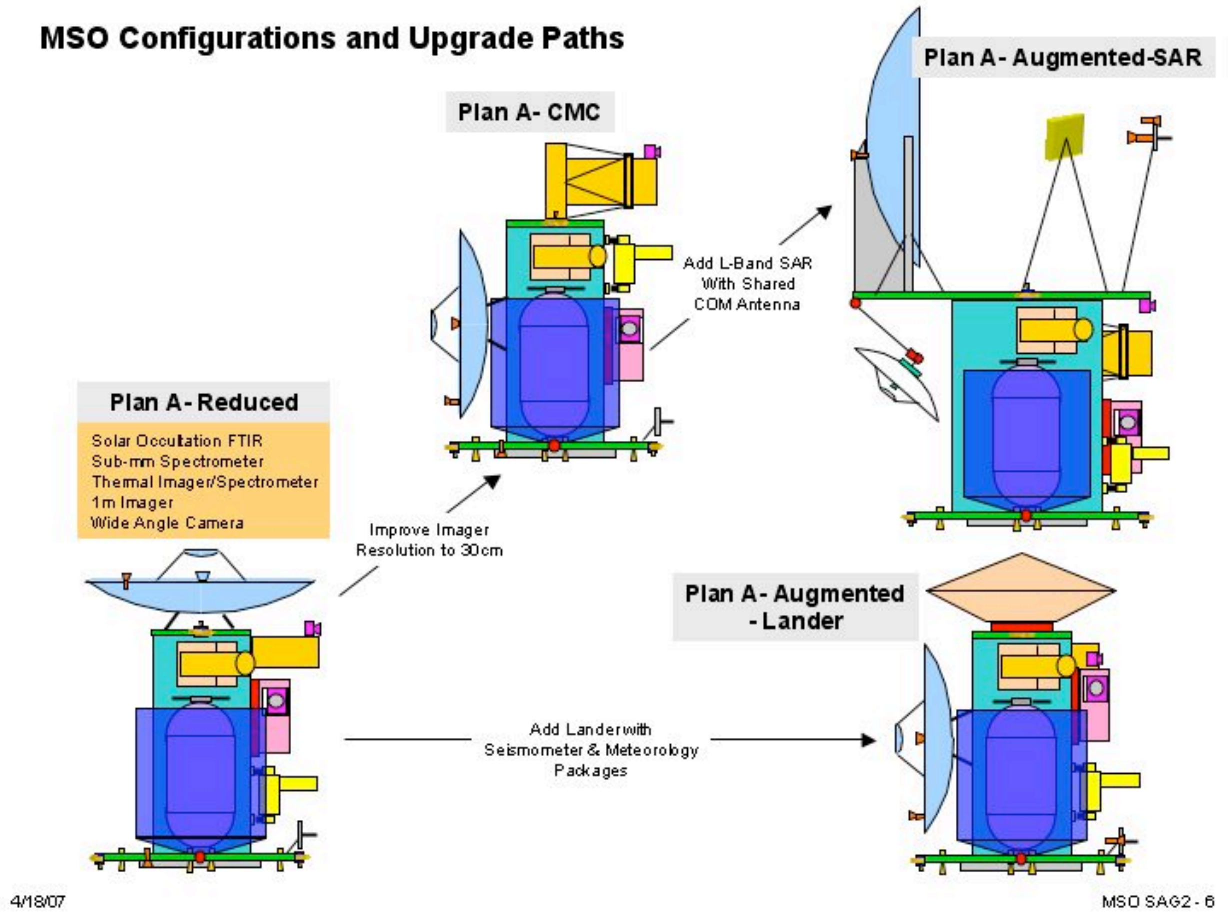
Table 9.2 Spacecraft Configuration

MSO Nomenclature	*OS*	*FSO +*	*OS + Adler NL*
S/C Characteristics		**Augmented to Accommodate P/L Complexity**	
256 Gbit storage	X	512 Gbit	X
1400 W EOL	X	2000 W EOL	X
Reaction wheels	X	+ Larger reaction wheels	X
10yr Ka/X/UHF; 14 (Max range)-100 Gbit(1AU) per 8hr pass	X	+ Gimbaled X-band antenna	X
Launch mass: 2900 kg	X	+ 600 kg	+ 300 kg
Atlas V 411	X	Atlas V 521 Fairing for SAR Accom.	X
Mission Characteristics			
I&T	X	Incr $	Incr $
Mission	X	Incr $	X

The currently considered operational scenario assumes a "turn to Earth downlink" strategy to reorient the spacecraft to communication with the DSN. This strategy avoids the risk/cost/mass penalties for precision pointing of a large gimbaled antenna with outboard Ka-Band amplifiers.

The network lander (the single pathfinder) studied was taken as a "black box" originating from several studies done in the recent past of rough and hard landers, and actually flown systems. This limits the option space to impact velocities greater than 10 m/s and acceleration from a few hundred to ~2000 g. The mass ejected from the orbiter prior to the MOI is of the order of 200 kg, including mass margins, which includes a landed payload of the order of 5 kg. The total notional costs of the network landers considered by the MSO team were of the order of $200 M which includes the accommodation on the spacecraft and the mission, landed payload, and reserves. The notional estimates of the landed payload cost included in the total are of the order of $10 M.

The following figure depicts a notional configuration for the spacecraft, assuming the Mission Scenario Plan A. From the “Reduced” version paths to accommodate the HCI, SAR or landed science are shown.



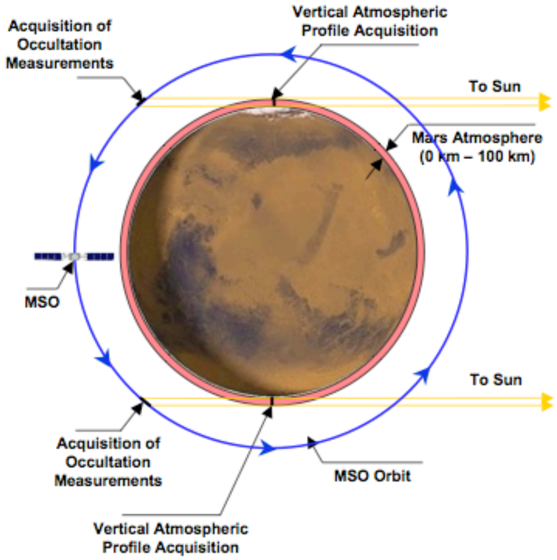
9.3 *Mission Design Trades*

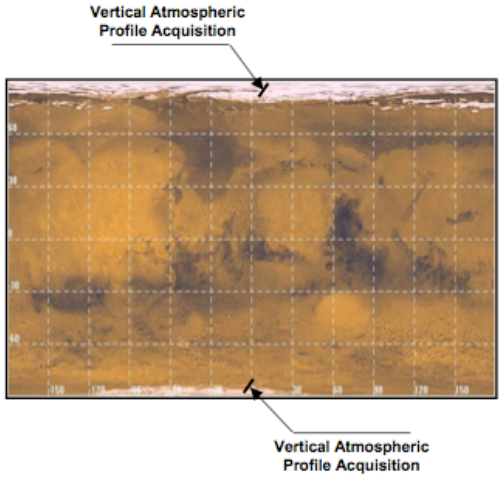
The MSO orbit will be near-polar, with ~ 80˚ to 95˚ inclination. A high inclination orbit allows access to the entire planet. However, the precise inclination desired by individual instruments depends on their viewing requirement. Typically, nadir-pointing instruments prefer polar inclinations (≈ 90˚), while others, particularly the solar occultation FTIR needs to be at lower inclination as described in Section 8.

The inclination for a sun-synchronous orbit is 92.6˚ at 300 km altitude, and 92.9˚ at 400 km altitude. The Local Mean Solar Times (LMST) can be chosen, such as the 3pm – 3am MRO orbit (although not all LMSTs will be possible). The sun-synchronous orbit has benefits, such as increased thermal stability of science instruments, reduction of thermal impact on the spacecraft and its operation, and favorable conditions for detector cooling. However, in addition to instruments desiring observations at varying LMSTs, non sun-synchronous orbit inclinations are required for critical events coverage.

9.3.1 Solar Occultations Study

In order to be able to compare orbital requirements of solar occultation instruments to others, a brief study was undertaken to outline the sensitivity to inclination and altitude. The limb occultation geometry is depicted below.





An occultation is defined as the passage of the line of sight from the S/C to the Sun passing through the atmosphere at the limb of Mars as seen from the S/C over a range of altitudes from 0 km to 100 km (for a Sunrise event; reverse direction for a Sunset event).

The parameters of interest are:

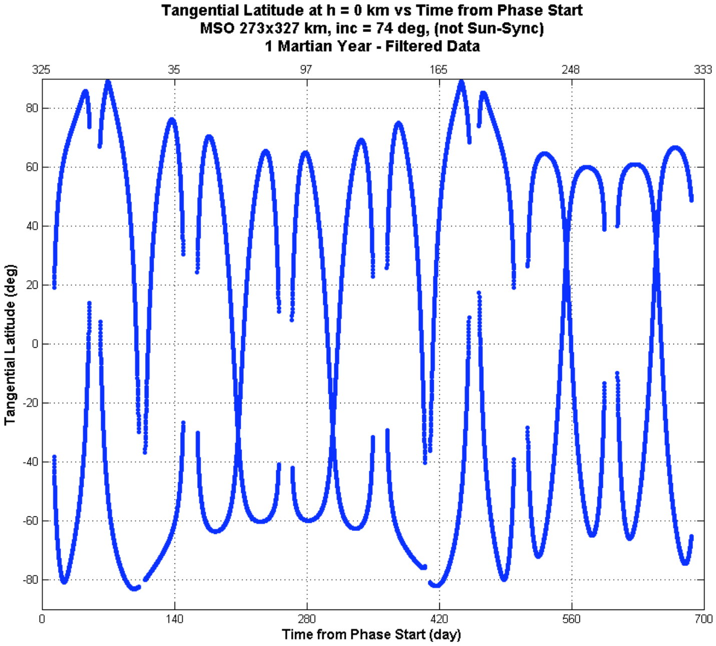
- Latitude of Atmosphere at the Limb at 0-km altitude for all occultations - plotted chronologically
- Latitude vs. Longitude of Atmosphere at the Limb at 0-km altitude for all occultations
- Duration of all occultations - plotted chronologically
- Projected Distance on Mars Surface of the separation of the locations of the atmosphere at the limb for 0 km alt. and 100 km alt. for all occultations - plotted chronologically.
- Local Mean Solar Time of Orbit Node plotted chronologically for 1 Martian Year
- Longitude of the Sun (Ls)

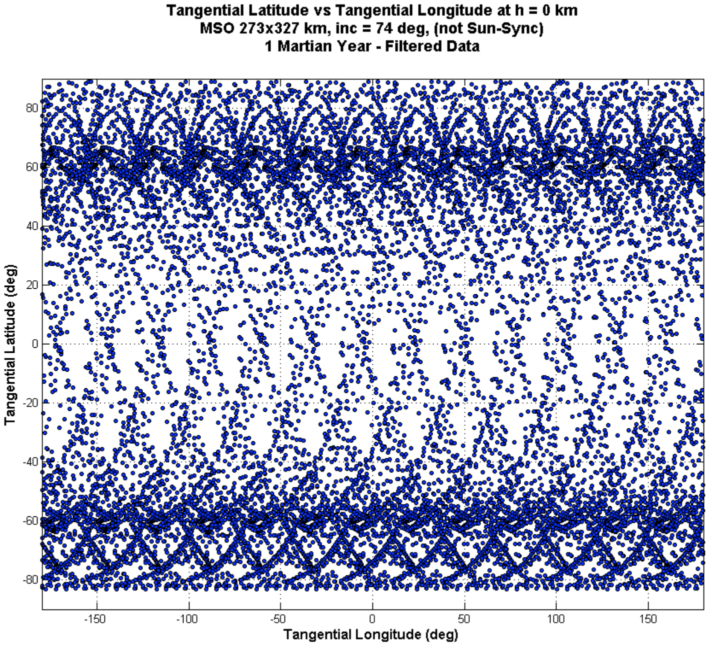
The required observing conditions: Limb crossing durations > 50 s with projected ground distances < 1000 km.

The parameters were determined for an MSO in a quasi-circular ("frozen") orbit at altitude 273 x 327 km, with non sun-synchronous inclinations of 74°, 80°, 82.5°, 85°, 87.5°, plus a sun-synchronous inclination of 92.6°.

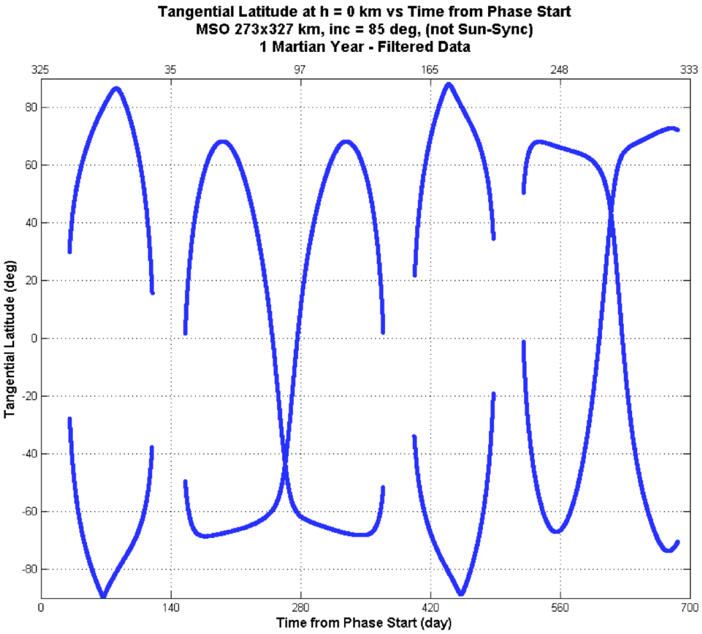
The results of study for 74° inclination (optimal for occultation opportunities) are plotted below, in terms of latitude at the limb and latitude vs. longitude coverage. In this orbit a wide range of latitudes is visited repeatedly, from season to season. Such repetitive coverage is desirable for atmospheric signatures measurements, as described under Mission Scenarios in Section 8.1.

Inclination 74°

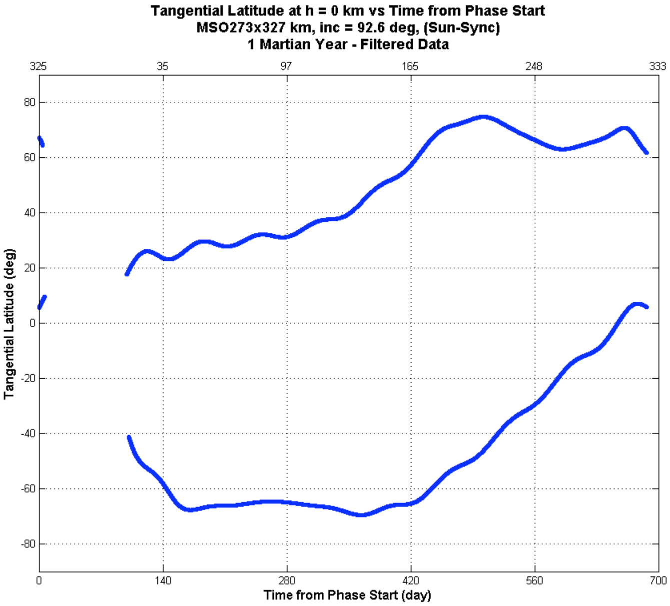




Inclination 85˚: An orbital inclination between sun-synchronous and 74˚, for example 85˚, represents a compromise that may be acceptable for the solar occultation, the nadir pointing instrumentation, and the spacecraft thermal considerations. This example was considered for Plan G, Section 8.3.


Tangential Latitude at h = 0 km vs Time from Phase Start
MSO 273x327 km, inc = 85 deg, (not Sun-Sync)
1 Martian Year - Filtered Data

Inclination 92.6˚ (Sun-Synchronous): While desirable from an operational point of view (e.g., thermal), a sun-synchronous inclination does not provide any latitude coverage near the equator for occultation-based measurements during any one season, and is therefore an undesirable orbit from the point of view of trace gas measurements.


Tangential Latitude at h = 0 km vs Time from Phase Start
MSO273x327 km, inc = 92.6 deg, (Sun-Sync)
1 Martian Year - Filtered Data

9.3.2 Lander Accessibility

The region of accessibility to a lander depends very strongly on the particular launch dates and arrival dates, as well the entry characteristics (entry speed, entry flight path angle, atmospheric descent phase) of the lander itself. For the current baseline launch period, which is optimized for mass deliverable into Mars orbit, and for entry characteristics similar to MSL's we would have a maximum northern latitude of 30°, maximum southern latitude of 85°, and an inertial entry speed of 5.9 km/s.

If, for example, accessibility is an important factor outside of this region, or if this entry speed is too high for particular technologies, then further mission design work is required and could significantly affect the mass performance and the appropriate launch vehicle, amongst other factors.

9.4 *MSO Implementation*

Notional science payload costs for the "OS", "FSO+", and "OS+NL" options were estimated by the MSO project using the following assumptions:

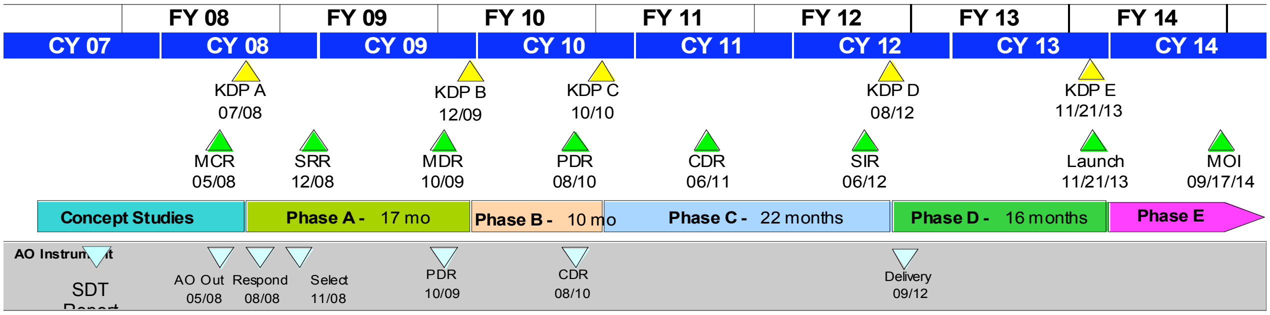
- The cost includes development and delivery of the flight instrument (Phase A-D, No Phase E)
- The costs are in constant FY06 $s
- No $ reserves are included (Project holds 30%)
- The costs do not include science management and the office of the Project Scientist

The cost estimate of the "OS" option is consistent with an MRO-class mission. "FSO+" and "OS+NL" are consistent with possible budget augmentations being discussed with HQ. The "OS" science payload is estimated notionally at $110 M. The "FSO+" and "OS+NL" are of the order of $180 M, and $190 M, respectively. The "OS+NL" payload cost estimate includes not only the cost of the landed science payload but also the total cost of the drop-off-package that is jettisoned prior to the MOI. As noted, no reserves are included in these costs. Depending on the specific design of the drop-off-package, a technology development program may have to be initiated to advance the drop-off-package technology readiness to level 6 by the Project PDR. These potential technology development costs are not included.

The dry mass of the MSO flight system, consisting of the spacecraft and science payload, was estimated at 1350 kg, 1650 kg, and 1600 kg for options "OS", "FSO+", and "OS+NL", respectively. The mass margin included in these mass estimates is 30% of the total allocation, or 43% of the nominal current best estimate (CBE). The science payload masses included in the totals are of the order of 170 kg for options "OS", 250 kg for "FSO+", and 370 kg for "OS+NL". All three options are within the capability of the Atlas-V 4x1/5x1-class launch vehicles for the 2013 Mars launch opportunity. The "OS+NL" payload total consists of orbital science payload of 170 kg plus a drop-off-package of 200 kg, which includes approximately 5 kg of landed science. All payload masses include contingency.

9.5 *Schedule*

The MSO development schedule (below) supports an orderly approach to the development of a planetary mission with competitively selected instruments. The development phase durations and associated products are based on NASA project management requirements and lessons learned from recent planetary missions. The most important early schedule milestones are the Instrument Announcement of Opportunity release in February 2008 and the Mission Concept Review in May 2008. Preparations for these key milestones depend on timely determination of the mission science objectives and conclusions of the Science Definition Team. The approach is designed to minimize the risks inherent in the development cycle of competitively selected instrumentation, in order to fulfill NASA's goal to produce landmark science while staying within cost boundaries.



9.6 *Summary*

In summary, mass and cost evaluation by the Project shows that all Core Mission Concepts and "Reduced" SAG-2 Plans fit within the resources range being considered by the Mars Program. The resources range in science payload cost terms from MRO-class to MRO x 1.6. The SAG-2 "Plan A Reduced" cost and instrument selection is similar to Project's MRO-class Strawman, Option "OS". SAG-2 "Plan A Augmented " is similar to Project's "FSO+" option, and included accommodation of a SAR. The Project option "OS+NL" adds a simple lander system to the baseline "OS". In cost terms this latter option is comparable to "FSO+"

10 Observations in Support of Future Exploration

10.1 *Landing Site Hazard Assessment*

The SAG-2 was also requested to study major science drivers and requirements for a camera system on MSO, with additional input on the "programmatic" need for characterizing future landing site hazards. Much of the first part of this analysis was included in the overall study of scientific investigations above, where visible-wavelength images play a significant role. The landing site issues were addressed through input from members of the SAG-2 and others currently involved in the site selection for Phoenix and MSL. At a broad level, the sub-group examined three possible options for camera capability: 1-m/pixel resolution, 30-cm/pixel resolution similar to HiRISE, and a 5-10 cm/pixel capability not yet demonstrated in Mars orbit. Landing hazard assessment has changed dramatically based on 30-cm/pixel resolution rather than 1.5-m/pixel resolution images, as evidenced by the shift in Phoenix landing sites after HiRISE imaging discovered numerous meter-scale boulders in areas previously thought to be safe. Given current requirements for landing safety (size of error ellipse and maximum scale of tolerable rocks given EDL system capabilities), a 30-cm/pixel capability for imaging future landing sites is well justified. There was no consensus that 5-10 cm/pixel image resolution was required for landing *safety*, though cogent arguments are presented above for the scientific value of such observations.

The ability to re-image sites over a wide variety of illumination angles enables significantly greater information and understanding of small-scale features than imaging at the same resolution and SNR but with a fixed local mean solar time (LMST). This was studied and simulated in detail for the Mars Rover Sample Return report on orbital imaging requirements (Bourke, R. et al., 1989). Alan Delamere (Ball Aerospace) constructed a laboratory Mars model and imaged it under variable illumination. Steve Squyres selected the field sites and photography and led that analysis. One of their major conclusions was that features near the resolution limit can be detected and understood if imaged under multiple sun elevations and azimuths. The Artificial Intelligence community has developed what they call "photometric stereo", in which 3 images of a scene with different illumination geometries are used to extract albedo, slope, and strike of each pixel (Wolff et al., 1992). Geometric stereo derives topography for an area of typically 4x4 or 5x5 pixels, so photometric stereo can provide quantitative topographic data at 4-5 times higher planimetric resolution from comparable image resolutions. So significantly improved characterization of key locations (candidate landing sites, potentially-active gullies, etc.) is possible with a migrating LMST, without the expense of a larger telescope.

In addition, current-generation analogue waveform-based laser altimeter methods can facilitate few cm resolution vertical roughness measurements across the scale of the measurement footprint; swath imaging lidar altimeters have been demonstrated that facilitate direct (deterministic) measurement of cm-scale vertical roughness across footprints in the 1 to 10m range, thereby adding significantly to what can be derived from imaging alone. Such methods may be applicable for characterizing and identifying safe landing zones on Mars for human exploration at scales required for mid L/D-based landing flight systems. Instruments considered in the trade space for MSO include multibeam lidar altimeters with waveforms that facilitate measurement of 1-5cm scale vertical roughness at the 10-20m footprint scale.

10.2 *Atmospheric Environment for Flight Aerodynamics*

The utility of observation of the atmospheric environment has been demonstrated with regard to aerobraking by MGS, ODY and MRO and with regard to entry, descent and landing (EDL) by MER and in the planning for PHX and MSL. Later landing or aerobraking systems, including components of MSO itself, also require a proper characterization of atmospheric environments likely to be encountered. Continued characterization of the lower atmosphere will aid design and implementation of EDL and precision landing for future landers and for vehicles employing aerocapture or prolonged atmospheric passage, including the much larger vehicles required for human exploration of Mars. Early work on the latter has already highlighted the need for atmospheric data bases because critical design issues must be addressed in the coming decade for missions that will not launch until much later (i.e., well after 2020).

Accelerometer measurements by MSO will be used in its aerobraking phase and will provide additional data for characterizing the upper atmosphere in a different combination of Mars year, season, and solar cycle. These accelerometer measurements should be preserved as a scientific data set and can then be used to improve models of upper atmosphere structure and circulation, as these provide the means to extrapolate to times and places not directly observed.

A key factor in the design, testing and actual EDL of landing spacecraft has been wind and its variation in space and time. Typically, entry vehicles have vulnerabilities that are sensitive to medium and small-scale (mesoscale) features of the wind field. This is complicated by the fact that near-surface winds are particularly sensitive to the substantial influence of local topography. Given the virtual absence of direct wind measurements on any scale, it has been necessary to depend upon numerical models of the wind field and theoretical extrapolations from these to scales (<= 1 km) that remain unresolved even in these. It is unlikely that, with the technology available today for flight to Mars, wind can be measured directly with the precision and resolutions required to support flight design and simulation. However, the direct measurement of winds at larger scales, even at modest precisions (e.g., 10 m/s averaged over 10-km layers), would provide a powerful constraint on the models used to simulate the finer-scale features. These measurements are most useful for validation when made in combination with profile measurements of aerosols and temperature. Then both the model drivers and the model response are independently constrained. MSO could provide this capability.

While half-scale height vertical profiles of aerosols are sufficient to provide improvement to our understanding of the forcing and responses in the atmosphere, the multi-beam lidar would be a much more rich dataset with which to explore the atmosphere's aerosol processes. Its ability to yield aerosol profiles with 100m vertical and 1km horizontal resolution from the surface to ~50km is well matched to both the scales of the phenomena in the atmosphere, as well as the scales of the models. In this way, the multi-beam lidar could provide significant constraints to further tune the atmospheric models.

The landed meteorological instruments considered can also have a big impact on the improvement of mesoscale and global models. These instruments represent a new class of observations over previous landers that would increase insight into, and provide validation of, the physical parameterizations used in models calculating near-surface fields. While the landed observations themselves are not globally representative, a model that has been properly tuned using these data can be more confidently applied across the globe. The result would be a significant improvement in the fidelity of mesoscale models to predict landing conditions.

Continuation of the weather monitoring, and of the temperature, dust and water climatology for several more Mars years would significantly increase the probability that the full range of environmental conditions to be encountered would be captured, as Mars varies from year to year. Finally, for those missions arriving while MSO is actively operating on station, the temperature profilers and atmospheric monitors would provide near-real-time observations of atmospheric state that would permit updates to critical EDL or aeropass parameters, as was done for MER and all the aerobraking orbiters.

10.3 *Precursor measurements for future human exploration*

In 2005, NASA's MEP and MEPAG formed a subcommittee to examine precursor measurements needed to reduce the risk of future human exploration missions to Mars. This Mars Human Precursor Science Steering Group (MHP-SSG), identified and prioritized these needed measurements. Many MSO science measurements directly address these exploration program needs. The table on the next page identifies the specific exploration investigation as identified by the MHP-SSG and MSO's potential corresponding complementary capability. We note that MSO could make advancements in nearly every one of exploration's top priorities. Other Exploration Systems Mission Directorate engineering needs are coupled to flight system design trades associated with human access to Mars. These are summarized below (and are not listed in the MHP-SSG table).

Additional knowledge requirements for human exploration of Mars (and of the Moon) have been identified in recent ESMD engineering documents, as derived from ESAS studies during 2005-2007. Ongoing design reference mission studies by a Mars Architecture Working Group (2007) are developing revised engineering knowledge requirements to facilitate human missions to the Martian surface. Included in the set of evolving requirements is the requirement for a global control network of ground control points (all within a center-of-mass reference frame, aka areocentric) to permit ALHAT algorithm development, testing and certification for human landings. ALHAT is the set of procedures to allow for precision, autonomous landings of human-rated flight systems on Mars, as is under development at NASA's JSC (with Draper Labs) for the human return to the Moon. Development of a global, center-of-mass referenced topographic model (DEM) for Mars with sub-meter vertical accuracy at horizontal scales (globally) of 100m or finer is a key element of the ALHAT approach. Suggested MSO instruments could facilitate development of this legacy dataset for both engineering of human landings (and landing algorithms) as well as for regional-global scale scientific investigations as summarized above. Finally, in situ resources and ISRU capabilities are one variable under consideration by ESMD engineers to enhance and facilitate human exploration of Mars. MSO instruments could begin the process of resource identification and localization via high-resolution studies of accessible water ice deposits in regions where human exploration may be preferred for scientific and safety reasons. MEPAG has sponsored a committee (HEM-SAG) to examine science and related goals for human exploration as inputs to the ESMD engineering process in 2007. Several issues associated with localization and understanding in situ resources, and in particular water ice concentrations within an accessible control volume, are under discussion. MSO instruments such as high-resolution multi-polarization SAR or high-resolution neutron spectrometers, as well as SWIR/TIR mineral mapping can contribute to this goal.

Exploration Investigation (Beaty et al., 2006)	Complemented by MSO
Characterize the particulates that could be transported to mission surfaces through the air	Atmospheric state sensing devices like Thermal-IR, and MARCI-like imagers will monitor density and flux of airborne dust activity over seasons; additional insights from the landed met package and the atmospheric lidar.
Determine the variations of atmospheric dynamical parameters from ground to >90 km that affect EDL and TAO	The orbital atmospheric state instruments, combined with the landed met package represent a nearly complete set of instruments to address this goal.
Determine if each Martian site to be visited by humans is free of replicating biohazards	While a definitive measurement of a highly bioloaded site would require a landed mission, some inferences might be obtained via the atmospheric signature packages, though more sensitivity may be required.
Characterize potential sources of water to support ISRU for eventual human missions.	Many elements of the MSO suite contribute to the determination of water sources, including MARCI, Thermal-IR, SWIR, Cameras, SAR.
Determine the possible toxic effects of Martian dust on humans.	While a sample return mission is required to definitively determine the soil toxicity, trace gas instruments may infer the presence of harsher chemical species created by dust; advanced active systems could resolve species at km scales to isolate potential vents.
Derive the basic measurements of atmospheric electricity that affects TAO and human occupation.	Electric field system on the MET landed package will provide the first-ever assessment of Martian atmospheric electricity
Determine the processes by which terrestrial microbial life, or its remains, is dispersed and/or destroyed on Mars	While a definitive measurement of a highly bioloaded site would require a landed mission, some inferences might be obtained via the atmospheric signature packages. More advanced active optical systems may be required.
Characterize in detail the ionizing radiation environment at the Martian surface,	N/A
Determine traction/cohesion in Martian soil/regolith	Thermal IR mineral mapping can determine the compositional nature of various regions, providing some inference on soil physical properties; multiple polarization surface lidar observations can constrain particles sizes and local slopes and roughness at 1-5 cm scales. High-resolution (30 cm/pixel) images can identify sand or dust deposits based on distinctive morphologies.
Determine the meteorological properties of dust storms at ground level that affect human occupation and EVA.	Landed MET can provide direct insight into weather conditions at ground during atmospherically unstable periods.

11 Discussion and Issues

11.1 *Science Issues*

Despite extensive discussion and scientific wrangling, further reduction of the three plans to one "highest priority" scenario was simply not possible. Although there are overlaps, each of these three scenarios pursues a different primary objective, with a different follow on to the Mars Exploration Program in the years after 2013. The discussion below captures several scientific issues and their resolution, where achieved. In the end the SAG-2 membership has high confidence that any one of these three scenarios will return significant and important and **new** information relevant to our understanding of the planet, its history and its potential for life, as described related to each plan in Section 8.

11.1.1 Subsurface Imaging

Concerns regarding the subsurface imaging investigation, and not necessarily with how it is accomplished, center on whether a view below the surface will be truly revealing, arguing that we can instead simply infer the subsurface geomorphology over large areas from occasional surface outcrops or from muted topographic signatures. The outcome of a fundamentally new investigation cannot be fully predicted, but terrestrial, lunar, and Martian subsurface probing to date strongly suggest that significant insights will result.

11.1.2 Methane detection and traceability

There was considerable discussion within the SAG-2 on two points: (1) What is the value of an Atmospheric Signatures investigation if methane is not detected? (2) If atmospheric measurements detect a trace gas indicating ground geochemical or biogeochemical activity, can a surface source be localized sufficiently well that a future mission can follow-up on that discovery?

With regard to the first question, the proposed measurement requirement would establish whether atmospheric methane was present at levels far below what has been reported to date or can be detected in the future (e.g., by MSL). This will remove any ambiguity of the reported discovery. However, the more important point is that active subsurface processes could have atmospheric signatures other than methane, so that it is a suite of trace gases that is targeted. Furthermore, it will be their relative abundances that help discriminate between the processes that produced them and that indicate, by analogy with Earth, if their source is more likely to be biochemical or geochemical in nature.

The second question—could one find a local source if it existed—was also debated among the SAG-2 members. The ideal would be to locate a source area with sufficient precision that it fits inside a precision landing ellipse (e.g., <10 km diameter circle) for a successor mission. This is not likely to be achieved given the rapid mixing in the Martian boundary layer and the rapidity of redistribution by the general circulation, even for signature species with a relatively short atmospheric lifetime. However, there is a strategy in which progress can be made in localizing the source, within the range of instrument resources considered by the SAG-2 to be practical for an MSO payload.

This strategy was captured in Scenario A: 1) Choose an instrument (e.g., the FTIR) with the sensitivity to detect a suite of trace gases (the atmospheric signatures), 2) Map (e.g., with the sub-mm spectrometer) a select few trace gases with denser coverage (but typically less precision) than solar occultation measurements can provide, 3) Observe winds, temperature and dust opacity in order to validate and drive transport models that can do the final tracing to more localized areas, and 4) Image the surface of these potential source regions to further isolate likely points or locales of origin.

11.1.3 Higher Spatial Resolution than HiRISE

The SAG-2 discussed the scientific return from imaging at significantly better spatial resolution (and comparable signal-to-noise ratio) than HiRISE (30 cm/pixel at 300 km altitude). This resolution can help resolve fundamental issues with regard to active processes such as gullies, and provides imaging at the equivalent of lander scales at many more sites than we will be able to land at during the coming decade. State of the art visualization can effectively show the surface view in these extreme high-resolution views. Similar techniques are actively being used for navigation of MER from HiRISE images. Unfortunately, achieving spatial resolution of 5-10 cm, under current state of the art, increases both mass and cost significantly, and largely becomes the only scientific goal for MSO. Also, spacecraft stability could become the limiting factor in resolution rather than the telescope. We discussed the possibility of "shared optics" i.e. a view similar to the space telescope where a single optic is shared by multiple instruments, but the practicalities of creating multiple optical chains were seen as prohibitive for the MSO mission. Though discussed at multiple stages in the process, the majority did not condone a "single instrument" core mission and so this option was ultimately dropped.

11.1.4 Seismic detection.

Concerns were expressed that the landed geophysics, in particular the search for seismic events might not result in a detection. It is recognized that expected number of detections goes down (and the risk of non-detection goes up) with just one landed package, and there is geometric growth in return with each station added. There has been a great deal of published work to estimate the expected rates of events from the cooling rate and predicts of seismic energy released, from historical faulting rates, and from extrapolating between the observed activity on the Moon and Earth. Based on these various approaches all agree that we should expect a few dozen globally detectable quakes/year (+/- an order of magnitude), with a reasonable expectation of many more regional and local events (assuming a seismometer with the sensitivity described in Table 6.4). The recently discovered MGS-era impact features provide direct evidence for ~10-20 significant seismic events per year. The Viking negative result is consistent with these estimated rates given the sensitivity of that seismometer and its duty cycle, as described in section 6.4.2.

The SAG-2 discussed whether a single drop package would remove the impetus to have a long-lived network for landed geophysics. The consensus is that in order to justify a full network mission a single measurement may actually be needed to provide better justification. If there really were a lack of results then the need for further measurements would indeed be questionable. A low rate of observed activity would require tough decisions about the value of future landed measurements.

11.1.5 Landed Science Priority

There was considerable discussion about how to best use the payload mass likely to be landed as a drop-off package from MSO [see also 11.2.1 below]. This resulted in a clear prioritization of the geophysics package instruments as follows: Seismometer, ranging for geodynamics, heat flow experiment. [The case for the seismic measurements was further discussed above in 11.1.4.] Prioritization between this geophysics package and an integrated meteorological package was more difficult. Comprehensive meteorological studies require data acquired from multiple stations dispersed over a wide variety of terrains. However, given the lack of detailed boundary layer measurements from anywhere on Mars, a single station would still provide a key data set for validating atmospheric models and their treatment (or resolution) of critical boundary layer phenomena. Such a station could also provide ground-level atmospheric truth for remote sensing observations (as in an augmented Plan A—see Table 8). The geophysics package gained a preference in that it begins to fill an enormous gap in our knowledge about Mars and its results are likely to have a more profound effect on a future landed network. However, the return from an integrated meteorological package was judged to be so significant that the SAG supported its inclusion.

11.1.6 Neutron spectroscopy

Very late in the process a discussion of improved neutron spectroscopy emerged. Within the context of measurements that support the climate and polar processes theme (Plan P), high resolution neutron spectroscopy (HRNS) offers a means for mapping spatial variations in hydrogen (H) content within the polar regolith down to approximately one meter depths at perhaps 80-100 km scales, relative to the existing ODYSSEY 500km resolution observations. A higher resolution neutron spectrometer can observe the seasonally changing column densities of the seasonal ice cap at a higher spatial resolution, providing details about smaller features such as the Mountains of Mitchell or the amount of seasonal CO_2 ice that accumulates above the south polar residual cap. When combined with LIDAR measurements, regional CO_2 densities can be derived as a function of season, thus providing information about CO_2 formation and densification processes. Neutron spectroscopy can also be used to track the amount of inert gases in the atmosphere. In light of these issues, an augmented Plan P could include neutron spectroscopy as an alternative to SAR, but SAG-2 did not have time to deliberate this change.

11.2 *Technical/Cost Issues*

11.2.1 Trades Involving a Landed Drop Package

In the absence of a defined architecture for the delivery of the drop-package, the SAG-2 could not weigh cost-benefits of the landed package versus the orbiter package. The SAG-2 did feel that a significant payload of remote sensing instruments addressing one or more of the themes articulated in this report should be a defining attribute of an MSO mission; that is, the orbiter should be much more than just a carrier for the telecommunications and drop-package systems. This was consistent with the SAG-2's belief that no one "instrument package" should dominate the MSO mission. As the scenarios above attest, the SAG-2 felt the drop-package would produce significant and substantial science, particularly in combination with particular orbiter payloads. But there will be costs that the SAG-2 was not in a position to consider.

The other concern with regard to the landed package was whether the landed mass (projected as ~ 5 kg) would be enough to do a meaningful geophysical payload, let alone one combined with an integrated meteorological package. The payload must include a capable seismometer with an X-band transponder needed for geodynamical ranging as a close second in priority. While even a single high-precision pressure sensor would return valuable data, the integrated meteorological package is needed to provide new insights, not only for the fundamental atmospheric science at Mars, but also for landing safety considerations of future missions as well. Increasing the landed capability to ~10 kg would significantly enhance the scientific return of the drop-package, more fully justifying the cost of its inclusion in the mission.

11.2.2 Budget Reserves

By design, each of the scenarios presented above include new measurements for Mars. Although an "existence proof" is indeed available for each one of the new capabilities, adaptation to flight on a Mars spacecraft may well entail considerable development. Thus, a now traditional payload reserve margin of ~30% may not be adequate, depending upon the number of innovative instruments and the desire to extend capabilities even of previous Mars instruments. The SAG-2 suggests that the Science Definition Team take a careful look at the capabilities to be requested in the future AO for MSO and scope the reserve accordingly.

11.2.3 Funding of Science Activities during Development (Phases A-D)

Science team activities during Phases A-D would include: 1) conduct critical pre-flight instrument calibration and testing, 2) prepare for safe commanding of the instrument and monitoring of its health after launch, and 3) prepare the ground data systems needed to further calibrate and operate the instrument once it is in orbit around Mars and 4) to analyze the data acquired. It was not clear to the SAG-2 whether these development phase science costs have been included appropriately. One safeguard is to ensure that the instrument development costs do not overrun (see 11.2.2 above) and eat into these preparation costs. The Science Definition Team should estimate these costs based on the capabilities required and the complexity and desired schedule of product delivery.

12 Conclusion

The exploration of Mars is in the midst of a scientific revolution brought forth by a major commitment by NASA to a sustained Mars Exploration Program (MEP) with a high flight-rate and a continuous flow of remarkable data. In spite of this major investment, Mars remains an enigma, with diverse scientific "gaps" that remain in the era beyond MRO and other missions. To think that the science that can be achieved via orbital remote sensing is all but over is now viewed as folly. Thanks to the ongoing MEP, we can describe several essential lines of scientific strategy that must be evaluated as the keystones for a 2013 MSO mission. There is no one "answer" to what must be accomplished by a 2013 MSO mission, in part because of the complexity of the Mars "system" that deserves investigation. Simple questions about sources and sinks of volatile species that could be tied to the history of biology on the planet cannot be addressed, nor can the intricate workings of the modern climate cycles reflected in the polar regions be quantitatively described. Furthermore, there remain basic unknowns about the state of the interior and the hidden landscapes of the most recent geologic era, buried as they are by the ever-shifting deposits of dust and recycled volatiles.

Because of these profound and basic unknowns, the MEPAG-chartered MSO SAG-2 has developed a set of parallel pathways as potential lines of scientific focus for a major step forward in the reconnaissance of the Mars "system" in 2013. Each overlaps the other in distinctive ways, and hybrid missions could certainly be developed. However, each pathway emphasizes an essential line of scientific investigation that addresses a set of connected unknowns.

For example, one "pathway" focuses on a broad, planet wide inventory of diagnostic disequilibrium trace gases and aspects of the dynamics of the atmosphere that controls their spatial and temporal distribution. A second MSO "pathway" focuses attention on the energy and mass balance of the dynamic polar regions (and associated volatile reservoirs) of Mars, with attention to the fine-scale workings of surface processes. A final pathway emphasizes the state of the shallow (and deeper) interior as well as the geological signatures of past eras hidden by mantles of covering materials across the entire planet. Each pathway continues forward the capability to assess the safety and scientific worthiness of future landing sites.

A scientifically bold reconnaissance in 2013 will set the course for the MEP to cost-effectively target missions that must be accomplished starting in 2016 and on into the 2020's. That no single mission instrument complement addresses all of the largest knowledge gaps is not surprising. The same situation is faced in Earth science, for which the recently released NRC Earth Science Decadal Survey highlights 14 orbital reconnaissance missions needed to understand the Earth's dynamic systems. Why should Mars be any different?

References

Beaty, D.W., Snook, K., Allen, C.C., Eppler, D., Farrell, W.M., Heldmann, J., Metzger, P., Peach, L., Wagner, S.A., and Zeitlin, C., (2005). An Analysis of the Precursor Measurements of Mars Needed to Reduce the Risk of the First Human Missions to Mars. Unpublished white paper, 77 p, posted June, 2005 by the Mars Exploration Program Analysis Group (MEPAG) at http://mepag.jpl.nasa.gov/reports/index.html.

Bourke, R., et al. (Eds.), 1989, Mars Rover Sample Return Mission: Report of the Mini-Workshop on Orbital Imaging Requirements. JPL D-6442, 40 pp.

MEPAG (2006), Mars Scientific Goals, Objectives, Investigations, and Priorities: 2006, J. Grant, ed., 31 p. white paper posted February, 2006 by the Mars Exploration Program Analysis Group (MEPAG) at http://mepag.jpl.nasa.gov/reports/index.html.

MAPG (2006): Mars Advance Planning Group, 2006 Update to “Robotic Mars Exploration Strategy 2007-2016,” Unpublished white paper, 24 p, posted Nov. 2006 by the Mars Exploration Program Analysis Group (MEPAG) at http://mepag.jpl.nasa.gov/reports/index.html

NRC (2003), New Frontiers in the Solar System: An Integrated Exploration Strategy.

Wolff, L.B., S.A. Shafer, and G.E. Healey (eds.) 1992, Physics-Based Vision: Shape Recovery, Jones and Bartlett, Boston, 522 pp.

List of Acronyms

Acronym	Definition
ACE	Atmospheric Chemistry Explorer
AFL	Astrobiology Field Laboratory
AIRSAR	Airborne Synthetic Aperture Radar
ALHAT	Autonomous Landing and Hazard Avoidance Technology
AO	Announcement of Opportunity
ASTER	Advanced Spaceborne Thermal Emission & Reflection Radiometer
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation
CBE	Current Best Estimate
CMC	Core Mission Concept
COMPLEX	Committee on Planetary and Lunar Exploration
CRISM	Compact Reconnaissance Imaging Spectrometer for Mars
CTX	Context Imager
DEM	Digital Elevation Model
DOP	Drop Off Package
DSN	Deep Space Network
DTM	Digital Terrain Model
ECHOS	Electrical Charging Hazards Originating from the Surface
EDL	Entry, Descent, and Landing
ESAS	Exploration Systems Architecture Study
ESMD	Exploration Systems Mission Directorate
EVA	Extravehicular Activity
FTIR	Fourier Transform Infrared
GCM	General Circulation Model
GRS	Gamma Ray Spectrometer
HCI	HiRISE Class Imager
HEM-SAG	Human Exploration for Mars Science Analysis Group
HiRISE	High Resolution Imaging Science Experiment
HQ	Headquarters
HRNS	High Resolution Neutron Spectroscopy
InSAR	Interferometric Synthetic Aperture Radar
IR	Infrared
ISRU	In Situ Resource Utilization
I&T	Integration and Test
ITAR	International Traffic in Arms Regulations
JPL	Jet Propulsion Laboratory
JSC	Johnson Space Center
LIDAR	Light Detection and Ranging
LMST	Local Mean Solar Time
LOD	Length of Day
LOLA	Lunar Orbiter Laser Altimeter
Ls	Longitude of the Sun

MAPG	Mars Advanced Planning Group
MARCI	Mars Color Imager
MARSIS	Mars Advanced Radar for Subsurface and Ionospheric Sounding
MATADOR	Mars Atmosphere and Dust in the Optical and Radio
MATMOS	Mars Atmospheric Trace Molecule Spectroscopy Experiment
MAVEN	Mars Atmosphere and Volatile Evolution
MCS	Mars Climate Sounder
MET	Meteorology
MEP	Mars Exploration Program
MEPAG	Mars Exploration Program Analysis Group
MER	Mars Exploration Rover Mission
MEX	Mars Express Mission
MGS	Mars Global Surveyor
MHP-SSG	Mars Human Precursor Science Steering Group
ML3N	Mars Long-Lived Lander Network
MOC	Mars Orbiter Camera
MOLA	Mars Orbiter Laser Altimeter
MOI	Mars Orbit Insertion
MPF	Mars Pathfinder Mission
MSL	Mars Science Laboratory
MRO	Mars Reconnaissance Orbiter
MSO	Mars Science Orbiter
MSR	Mars Sample Return
NASA	National Aeronautics and Space Administration
NIR	Near Infrared
NL	Network Lander
NPLD	North Polar Layered Deposits
NRC	National Research Council
ODY	Mars Odyssey Mission
OMEGA	Observatoire pour la Minéralogie, l'Eau, les Glaces, et l'Activité
PDR	Preliminary Design Review
PHX	Phoenix Mars Mission
P/L	Payload
PLD	Polar Layered Deposits
POP	Program Operating Plan
REMS	Rover Environmental Monitoring Station
RMS	Root Mean Square
RSE	Radio Science Experiment
ROM	Rough Order of Magnitude
SAG	Science Analysis Group
SAR	Synthetic Aperture Radar
S/C	Spacecraft
SDT	Science Definition Team
SHARAD	Shallow Subsurface Radar
SNR	Signal to Noise Ratio
SPRC	South Polar Residual Cap

SWIR	Short Wave Infrared
TAO	Takeoff, Ascent, and Orbit
TES	Thermal Emission Spectrometer
TGE	The Great Escape
THEMIS	Thermal Emission Imaging System
TIR	Thermal Infrared
TRL	Technology Readiness Level
UHF	Ultra-High Frequency
USO	Ultra-stable Oscillator
VHF	Very High Frequency