# REPORT

## OF THE

# NASA

# SCIENCE DEFINITION TEAM

## FOR THE

# MARS SCIENCE ORBITER

# (MSO)

*December 15, 2007*

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## 1. PREAMBLE

NASA is considering that its Mars Exploration Program (MEP) would launch an orbiter to Mars in the 2013 launch opportunity. To further explore this opportunity, NASA has formed a Science Definition Team (SDT) for this orbiter mission, provisionally called the Mars Science Orbiter (MSO). Membership and leadership of the SDT are given in Appendix I. Dr. Michael D. Smith chaired the SDT.

The purpose of the SDT was to define the:

- Scientific objectives of an MSO mission to be launched to Mars no earlier than the 2013 launch opportunity, building on the findings for Plan A [*Atmospheric Signatures and Near-Surface Change*] of the Mars Exploration Program Analysis Group (MEPAG) Second Science Analysis Group (SAG-2).

- Science requirements of instruments that are most likely to make high priority measurements from the MSO platform, giving due consideration to the likely mission, spacecraft and programmatic constraints. The possibilities and opportunities for international partners to provide the needed instrumentation should be considered.

- Desired orbits and mission profile for optimal scientific return in support of the scientific objectives, and the likely practical capabilities and the potential constraints defined by the science requirements.

- Potential science synergies with, or support for, future missions, such as a Mars Sample Return. This shall include imaging for evaluation and certification of future landing sites.

As a starting point, the SDT was charged to assume *spacecraft* capabilities similar to those of the Mars Reconnaissance Orbiter (MRO). The SDT was further charged to assume that MSO would be scoped to support telecommunications relay of data from, and commands to, landed assets, over a 10 Earth year period following orbit insertion. Missions supported by MSO may include planned international missions such as EXOMARS.

The MSO SDT study was conducted during October – December 2007. The SDT was directed to complete its work by December 15, 2007. This rapid turn-around was required in order to allow time to prepare an Announcement of Opportunity (AO) for science investigations, to be released in early 2008.

The SDT met three times via telecon during October and early November 2007, before its main face-to-face meeting hosted at Caltech on November 12 and 13, 2007. Four additional telecons were held during November and December 2007 to follow up on issues left undecided at the Caltech meeting. During the telecons and face-to-face meeting, the SDT panel members discussed the scope of scientific objectives to be accomplished by the MSO and the resulting measurement requirements. The SDT also considered the potential likely combination of instruments that could credibly achieve the science goals to confirm that there were science payloads that fit within the given MSO constraints. The JPL MSO Project Team described a reference mission which included target payload mass, power, and cost envelopes; mission designs, including options for different orbital inclinations and heights; and issues and concerns regarding various payload instrument candidates, such as pointing requirements.

This report summarizes the activities and recommendations of the SDT. Section 2 gives a high-level summary of the findings of the SDT. Section 3 identifies the key science objectives and programmatic areas that the SDT believes should be addressed by MSO. Section 4 summarizes recommendations by the SDT regarding mission requirements. Section 5 describes and justifies the scientific objectives of the MSO mission, and lists a set of measurement goals. Section 6 describes a sample reference mission including orbit design and a sample instrument payload. Section 7 identifies a few concerns raised during SDT discussions. Supporting material can be found in the Appendices. In particular, Appendix 2 traces the MSO science questions and candidate investigations to corresponding MEPAG investigations.

## 2. EXECUTIVE SUMMARY

*The MSO SDT recommends that NASA fly an orbiter mission in 2013 that would largely follow the science goals and objectives of the "Plan A" mission (Atmospheric Signatures and Near-Surface Change) as described by the MEPAG SAG-2 report.*

The SDT recommends the following three main science drivers for the MSO mission: 1) A new and comprehensive view of **Atmospheric Composition** to seek evidence for the present habitability of Mars; 2) A vastly improved characterization of the present **Atmospheric State** to provide new insight into processes that control the martian weather and climate; and 3) An in-depth study of **Surface Change Science** to better understand the crucial interactions at the surface-atmosphere interface. In addition to the above science objectives, NASA may choose to include a very high (sub-meter) spatial resolution imager necessary for landing site certification and the telecommunications equipment necessary for MSO to serve as a long-term (10 Earth years) asset for the relay of data from, and commands to, future landed spacecraft. Scientifically, the inclusion of the sub-meter resolution imager would augment the range of surface change science that could be addressed, while the long-term telecommunications capability holds promise for an extended period of science operations to cover interannual variability. Both, however, may be beyond the funding envelope described for the mission without a major international contribution. Even without sub-meter scale imaging and extended scientific operations, the MSO mission defined below, with one-meter scale imaging and operating for at least one Mars year, would make major advances in the areas of climate and global habitability.

To achieve the atmospheric science objectives would require a capable suite of instruments, some with capabilities not previously flown to Mars. *The SDT recommends inclusion of remote sensing instrumentation with extremely high sensitivity to a broad suite of important trace gases combined with nearly continuous spatial mapping of key minor constituents and of atmospheric state.* As an existence proof that such measurements can be made, the SDT notes, based on instrumentation already flown to study the Earth's upper atmosphere, that a combination of solar occultation, limb sounding, and nadir mapping observations could provide the required two-tiered approach.

*To best achieve all science goals, the SDT recommends a near-circular, high-inclination orbit at an altitude of 300 km with an orbital inclination of 82.5°.* This relatively low altitude would allow the highest possible spatial resolution for imaging and limb-sounding while the inclination would strike a good balance between a rapid change of observed local time during the course of the mission (favored by lower inclination) and the ability to adequately observe the poles (favored by higher inclination).

*The SDT also notes that it would be necessary that the spacecraft be able to point accurately and with sufficient stability to regularly acquire solar occultation and limb-geometry observations as often as possible.* Furthermore, the continuity and global coverage of atmospheric observations on a repeated, daily basis necessary to fully realize the potential of the mapping portions of the investigations envisioned here would require that observations be able to be taken in a nearly continuous fashion (goal of ~85% coverage along the orbit track).

*The SDT endorses the planned Science Emphasis Phase, with one Mars year of observations with the science payload, but strongly recommends the goal of extending the phase with science observations to cover additional Mars years to fully leverage the scientific capabilities of MSO.* Presently, the Science Emphasis Phase would be followed by a transition to a near-circular, high-inclination orbit at a higher altitude of 400 km for the Telecom Emphasis Phase. The higher altitude satisfies planetary protection requirements, and would also be more desirable for telecommunications relay between Earth and future landed missions. MSO science observations should continue in this higher orbit.

The SDT recognizes that the full instrument suite given as a sample payload in Section 6 may exceed the baseline cost allocated to MSO science instruments. Cost could be reduced to fit within budget by the potential foreign contribution of an instrument or by descope of the instruments. In particular, most *science* goals could be met within budget if the proposed high-resolution camera were descoped from 30 cm to 1 meter per pixel resolution, although site certification requirements would not.

A concern sometimes expressed about MSO is that it would be too focused on a gas or suite of gases that might not be there. Such concerns arise in part from the continuing controversy about the detection (or not) of methane by ground-based or Mars Express observations. The SDT notes the following: 1) the atmospheric objectives of MSO as defined here would encompass a much more comprehensive atmospheric survey designed to characterize the variations of known gases (e.g., water vapor, peroxide, and carbon monoxide), as well as to improve *by an order of magnitude or more* the detection limits of gases not yet seen; 2) a measurement which could definitively state that methane is, or is not, present with a detectability threshold orders of magnitude more sensitive than the presently debated values *would be a major finding whether or not methane is detected*; and 3) the first direct, globally distributed measurements of wind and the measurements of temperature and water vapor even in a dusty atmosphere would yield a *major advance in our ability to understand and to simulate (for science and engineering)* the Mars atmosphere, its dynamic processes and transport.

# 3. MSO MISSION OBJECTIVES

Following the recommendations put forth by the MSO SAG-2 Report "Plan A" and the charge of MSO SDT Charter, the SDT identified five major objectives for the MSO mission:

## 3.1 Atmospheric Composition

The overarching goal of the Atmospheric Composition objective would be to seek atmospheric evidence for present habitability and life through a sensitive and comprehensive survey of the abundance and temporal and seasonal distribution of atmospheric species and isotopologues. It has long been understood that the presence of life on a planet could modify the atmosphere in such a fashion that this "disequilibrium" condition could be detected by remote sensing. Moreover, active abiogenic geological processes also will modify the environment in which these processes occur. The atmospheric signatures of active processes that might be present and at what abundances they exist are largely unknown. Thus, the recommended approach would be to sensitively search for a diversity of signature molecules so that, in addition to characterizing the variations of known minor gases over a broad range of temporal and spatial scales, the detection limits of key gases not yet (unambiguously) detected would be improved *by an order of magnitude or more*.

## 3.2 Atmospheric State

The Atmospheric State objective seeks to provide new insight into climate processes responsible for seasonal and interannual change. This would be accomplished by both providing new observations that constrain and validate models of atmospheric dynamics and state, and by extending the present record of martian climatology to characterize interannual variability and long-term trends of the atmospheric state, circulation, and cycles of dust, water, and carbon dioxide. New observations would include the first-ever direct observations of vertically resolved wind velocity over the globe on a daily basis, and broad coverage of the diurnal cycle of temperatures, winds, aerosol optical depth, and gas abundances. With these observations and the improved transport and climate models that would result from them, it would be possible to better describe surface-atmospheric interactions key to many climate processes, and may be possible to trace spatially varying minor atmospheric constituents (including water vapor) to localized source areas. Real-time monitoring of the atmospheric state would also play an important role in supporting the implementation of future spacecraft arrival and operation.

## 3.3 Surface Change Science

The surface science objectives of the MSO mission would be focused on surface change as recorded in surface properties and morphologies due to seasonal cycling of polar layered deposits, aeolian movement of fine material globally and locally, mass wasting, the slow accumulation of small impact craters and possibly the action of water even today in special regions of the planet. Observations with good signal to noise and a combination of spatial-temporal resolutions, from periodic global survey to high resolution imaging of particular areas of activity would continue to improve our understanding of modern processes of surface-atmospheric interaction and surface change and our ability to extrapolate them back into the recent geologic past.

## 3.4  Site Certification Imaging

Images taken by the HiRISE instrument on-board the Mars Reconnaissance Orbiter have demonstrated the value of high-resolution (~30 cm resolution) imaging for the purpose of site certification for future landed missions. The inclusion of a high-resolution camera with similar capability would allow the certification of new locations for potential landing sites that may be identified by new MSO observations. The SDT concurs that (sub-meter) very high resolution imaging would be required for landing site certification.

## 3.5  Telecommunications

The SDT endorses the plan for MSO to provide key telecommunications infrastructure over its planned 10 Earth year lifetime supporting the relay of science data from, and commands to, landed assets. MSO would also provide telecommunications coverage of future planned critical events such as EDL, Mars ascent vehicle launches, and MOI for other missions. This capability would add significantly to the science return and robustness of all future missions to Mars during MSO operations. Because it is likely that science and relay would frequently occur during the same mission phases, special care should be given to ensuring that the science payload and telecommunications packages could be operated concurrently with satisfactory results to both.

# 4. MSO MISSION REQUIREMENTS

***The SDT fully recommends use of the 2013 opportunity for launch of MSO to Mars***. The favorable energetics of this launch opportunity means that MSO would have sufficient mass margin to accommodate an ambitious payload (mass could also be used to reduce cost and cost risk) and could carry the fuel needed for a long-lived mission.  There would also be the potential for considerable synergy with the presently planned 2011 Mars Scout aeronomy mission operating in an extended phase, with simultaneous measurements in the upper and lower atmosphere nicely complementing one another. The provision of a robust telecommunications capability by 2014 could support a still working MSL and/or a newly arrived EXOMARS.

The following discusses other high-level requirements for the mission:

## 4.1  Operational Phases and Mission Life

MSO would perform its mission during two main operation phases:

- Phase One (Science Emphasis), consisting of a low (300 km), near-circular, high-inclination orbit compatible with science requirements, for a duration of at least 1 Martian year.
- Phase Two (Telecom Emphasis), consisting of a low (400 km), near-circular, high-inclination orbit compatible with planetary protection, as well as telecommunications support and long-term station keeping, for a duration of 7 Earth years.

In the context above, the term "emphasis" is used to highlight the idea that while priority is given to one kind of activity, the other would be executed as well, but on a best-effort basis. Thus, during the Science Emphasis phase, telecom tasks would be performed also, and during the Telecom Emphasis phase, science observations would also take place.

The nominal end of the MSO mission would be 10 Earth years after Mars Orbit Insertion (MOI).

## 4.2  Orbit Characteristics

Remote sensing measurements of the detailed composition and dynamics of the atmosphere favor near-circular orbits, with precession periods that provide full diurnal coverage on a time scale of one Martian season (about 6 Earth months) or less. A high-inclination (not Sun-synchronous), near-circular orbit at an altitude of a few hundred km would provide the best spatial, seasonal, and diurnal coverage, together with the required vertical resolution.

The SDT spent some time debating the optimal inclination and altitude of the MSO orbit. A study of candidate orbits by the JPL MSO Project Team showed that an inclination of 82.5° would provide a good compromise allowing for sufficiently fast cycling through local time, acceptable latitude distribution of solar occultation points (including pole-to-pole coverage), and the ability to image key parts of the polar regions (see also Section 6). The driving science requirement here would be that the local time of solar occultation points at each latitude cycle through a complete diurnal cycle in one Martian season or less. A lower inclination (e.g. 74°) would allow both a faster

precession of local time and a more uniform latitude distribution of solar occultation points, but would not allow the atmosphere above the rotational pole to be imaged and limits nadir-viewing mapping of the polar residual ice caps. A higher inclination (e.g. 85°) would be more favorable to polar surface imaging, but would have a poor latitude distribution of solar occultation points and would not cycle through local time quickly enough to distinguish between diurnal and seasonal variations in observed quantities. After much discussion, the SDT settled on a compromise inclination of 82.5˚.

An orbital altitude of 400 km would have the advantage of giving limb-to-limb coverage for wide-angle global imaging of atmospheric phenomena, whereas an altitude of 300 km would tend to leave small gaps near the equator in such coverage, but would provide higher spatial resolution. The SDT recommended the lower altitude pioneered by MRO.

*The SDT recommends this combination (~300 km, ~82.5˚) for the orbit to be advertised in the AO*, but recognizes that there will surely be some discussion on these parameters once the payload has been selected.

## 4.3  Science Observing Capabilities

The very high sensitivity required to allow the unambiguous interpretation for trace gas species (i.e. the identification of species and quantitative analysis at detection levels well below current upper limits) would likely be best achieved by exploiting the enormous source intensity and long path length of the solar occultation technique. *Therefore, the SDT highly recommends that the MSO mission plan maximize the number of solar occultation measurements possible, ideally two per orbit.*

A mapping capability complementary to the solar occultations would be a crucial element of the science plans endorsed by the SDT. Mapping requires the ability of instruments to be able to view both the limb (along-track and cross-track) and nadir at all points along the orbit. While specific operations, such as a pitch/roll to position for solar occultation or high-resolution imaging of landing sites, may sometimes require movement of the spacecraft that precludes the ability of mapping instruments to view nadir or the limb, *the SDT recommends a goal that such mapping be possible 85% of the time*. If possible, the gaps in mapping operations that do occur should be planned to minimize repeated loss of mapping at any particular latitude.

## 4.4  Archival of Science Data

Science investigations will provide to the project calibrated data within six months after its receipt on earth. The project will archive copies of all verified, validated, and calibrated data acquired by the mission to the Planetary Data System.

## 4.5  Infrastructure Objectives

In addition to its scientific objectives, the MSO would provide several infrastructure services to support future Mars missions. First, it is planned that MSO would establish a key

telecommunications infrastructure component for future Mars missions, providing coverage of critical events, significantly increasing the robustness and overall science return of the Mars Exploration Program, and enabling greater flexibility of Mars program planning. Using high-performance proximity and deep space links, MSO would offer increased amounts of science data return to Earth for all Mars missions flown during its operational period.  By providing access to energy-efficient relay links, MSO would allow user missions to reduce their telecom power and hardware requirements, leaving more delivered mass and power for science instruments. *The SDT endorses MSO's planned capability to provide telecommunications infrastructure.*

The SDT recommends that MSO provides atmospheric data that would support the design of aero-assist and EDL activities of future missions. Principally, the MSO science investigations would study the state, and the spatial and temporal variations (diurnal and seasonal) of Mars' atmosphere. The resulting increase of our knowledge of the atmosphere, and the increased fidelity of the numerical models (GCMs), would directly benefit the design of aero-assist and EDL activities of future missions. In addition, it is envisioned that near-real time monitoring of relevant atmospheric parameters (density, dust optical depth, etc) would provide essential information to MSO-concurrent spacecraft arriving at Mars. *The SDT recommends that MSO be capable of providing the relevant information at regular intervals as needed*, so that aerobraking or aero-entry trajectory parameters could be adjusted if necessary.

## 4.6  Planetary Protection

MSO will be compliant with NPD 8020.7 (Biological Contamination Control for Outbound and Inbound Planetary Spacecraft), NPG 8020.12 (Planetary Protection Provisions for Robotic Extraterrestrial Missions) and subsidiary documentation (COSPAR PPP) for planetary protection purposes.

## 4.7  Public Outreach

*MSO science investigations will provide to the MSO project science/technology data suitable for release to the public via the Internet.  The MSO project will assure regular releases for public information purposes in a timely manner.* The public releases are to convey the excitement and wonder of space exploration to the US taxpayer.

# 5.  SCIENCE OBJECTIVES

As briefly described in Section 2, the SDT divided the scientific objectives of the MSO mission into three main categories: 1) **Atmospheric Composition**, 2) **Atmospheric State**, and 3) **Surface Change Science**. Below are details of the justification and measurement goals for each science objective.

## 5.1  Atmospheric Composition

Measurements of atmospheric composition constitute a primary objective of the MSO mission, thereby enabling comprehensive study of the coupled volatile environment of the Mars atmosphere, surface, and subsurface. Time and spatially dependent exchanges among the photochemically active atmosphere, surface ice of the polar caps, and potential subsurface sources (water vapor in adsorbed or permafrost state, methane from biogenic or geochemical sources) remain poorly constrained due to the limited breadth and sensitivity of existing measurements. Hence, MSO atmospheric observations should include a baseline set of molecular species necessary to isolate the key photochemical, transport, condensation, and biogenic-geochemical processes that control the current chemical state of the Mars atmosphere. In many cases these observations would require exceptional sensitivities relative to prior mission capabilities. Most notably, detection-mapping capability for atmospheric methane presents a core requirement due to its potential as a biogenic marker. Key atmospheric priorities are identified for photochemistry ($H_2O_2$, $O_3$, CO, $H_2O$), transport (CO, $H_2O$), isotopic fractionation (isotopomers of $H_2O$ and $CO_2$), and surface-subsurface sources ($CH_4$ and $H_2O$). Additional targets of interest include $HO_2$, $NO_x$, and sulfur/carbon/ chlorine components associated with potential subsurface sources.

### Photochemistry

Mars photochemistry exhibits similarities to the terrestrial mesosphere in that $HO_x$ radicals ($H_2O_2$, $HO_2$, OH, and H) associated with water vapor photolysis exert catalytic control over the trace specie families of $O_x$ ($O_2$, $O_3$, and O), $NO_x$ ($NO_2$, NO), and CO. In the case of Mars, these trace oxygen, nitrogen and carbon constituents are produced through photo-dissociation of the bulk $CO_2$/$N_2$ atmosphere. Loss and partitioning rates are dominated by reactions with the $HO_x$ radicals $HO_2$, OH, and H; for which $H_2O_2$ serves as a short-lived (1000 seconds) reservoir (i.e., 2xOH). This link with $HO_x$ chemistry leads to a fairly direct correspondence of short-lived trace gas species with the variable distribution of atmospheric water vapor in space and time. Long-lived photochemical products (CO, $O_2$, $H_2$) should exhibit much weaker spatial and temporal variations in the lower atmosphere, associated with transport and condensation effects.

Existing observations of Mars CO, $O_2$, $O_3$, and $H_2O_2$ indicate the activity of homogeneous (gas-phase) photochemistry on Mars, but the data are insufficient to define the roles of heterogeneous, transport and non-equilibrium processes. These include heterogeneous loss of $HO_x$ on ice clouds, $HO_x$ production on charged dust particles, condensation and transport enrichment of species, and

subsurface sources/reservoirs. A much more detailed characterization of the spatial/temporal distributions of key photochemical constituents than currently supported by existing measurements is required to separate and so identify these processes.

*Measurement Goals:* A baseline set of MSO photochemical measurement objectives includes water vapor, $H_2O_2$, $O_3$, CO, water ice and dust aerosols. Other targets of photochemical interest are $HO_2$, $O_2$, $H_2$, $NO_2$ or NO, and $SO_2$. Baseline vertical profile ranges are 0–60 km for water vapor, CO, and dust and ice aerosol opacities; and 0–40 km for $H_2O_2$ and $O_3$, with 5 km vertical resolution. The sensitivity of the measurements (at 20 km altitude) should be 10 ppbv for water vapor, 100 pptv for $H_2O_2$, 1 ppmv for CO, and 1 ppbv for $O_3$. Nearly continuous global mapping capability is needed to characterize the dynamic variation of Mars atmospheric water vapor (and hence, the short-lived $H_2O_2$ and $O_3$ species), associated with surface and cloud ice formation and sublimation. Such mapping capability would also enable optimum observational constraints on potential heterogeneous chemistry associated with dust and ice aerosol variability, as well as potential subsurface out-gassing and adsorption.

## Methane and Other Subsurface Source Gases

In the earliest discussion of the detection of life on Mars, Hitchcock & Lovelock suggested that the presence of reduced gases, such as methane ($CH_4$), in an oxidizing atmosphere would be indirect evidence of life. Indeed, terrestrial microorganisms produce a wide variety of reduced gases as products of both energy-yielding oxidation-reduction (redox) reactions and synthesis and decomposition of organic matter. However, several geological processes may also inject reduced gases into 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.

The discovery of either extant geothermal or biological processes and their source locations would have profound implications for astrobiology and the Mars Exploration Program. 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.

A key objective of the MSO investigation would be to follow up on the reported observations of methane in the Martian atmosphere. Reports 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), or exchange with the surface/cryosphere 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. Thus, it

is necessary to map co-generated species that have much shorter atmospheric lifetimes and therefore could be tracers leading back to source zones.

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 co-generated 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 much less than unity for the former, while other sources produce more equivalent amounts of $CH_4$ and $C_2H_6$. Likewise, precise measurements of the carbon and hydrogen isotopic abundance (~10 per mil) of methane could provide insight into its putative source.

With respect to trace gas disequilibria, this investigation has four specific objectives:

- Identify chemical constituents in the atmosphere that cannot be formed by atmospheric photochemical processes (signature species). Besides the tentative $CH_4$ detections, other chemical signatures arising from possible active subsurface processes may be present in the atmosphere (e.g., $SO_2$).
- Locate source regions on the surface for these gases. Knowledge of a source region would provide direction for later missions.
- 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.
- Determine character of processes 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.

*Measurement Goals:* 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, the measurement requirement is to sensitively detect a diversity of 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, and thus state-of-the-art instrumentation approaches are required for their detection.

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; co-generated 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.

The search for atmospheric signatures must be global. 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 tens of meters to ~1 km. The detection of such plumes, therefore, would require 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 would 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 less than one scale height. Observation of a detectable signature gas with an appropriate lifetime (e.g., $SO_2$), could 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 (see Section 5.2).

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 would be improved by observations of the vertical distribution of composition, temperature, and dust (at half scale height, or 5 km, resolution). In addition, observations would be 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 at least one Martian year over a broad latitude range and with observations with full latitudinal coverage at least once per season to optimize detection of seasonal variability and more frequently to optimize detection of episodic events.

## Isotopic Ratios

Measurements of hydrogen, oxygen, and carbon isotopic abundance in the Martian atmosphere would allow new and important constraints to be placed on atmospheric chemistry, meteorology and interactions between the atmosphere and surface. Measurements of these isotopologues of

$CO_2$ and water vapor in the lower atmosphere of Mars would provide a boundary condition for aiding in the interpretation of the aeronomy measurements in the upper atmosphere planned for the proposed 2011 Scout aeronomy mission. Currently, knowledge of the isotopic composition of present day Mars is limited to low-precision Viking analyses and Earth-based spectroscopic observations of D/H ratio of Martian atmospheric water vapor and the ratio of D to H atom abundance in the exosphere. Additional, though less direct constraints are provided by measurements of ancient Martian volatiles in the SNC meteorites. While these measurements are significant constraints on models of long-term atmospheric evolution, the generally poor precision and lack of knowledge of the vertical and latitudinal isotopic variations of atmospheric gases limits their usefulness for answering specific questions about the internal dynamics of the Martian atmosphere and its interactions with the surface. Likewise for carbon, measurement of $^{13}C/^{12}C$ in atmospheric $CO_2$ would allow the anomalous observations of this ratio in SNC meteorites to be placed in the context of a well-mixed and large Martian carbon pool. Finally, latitudinally resolved observations of oxygen isotopes in $CO_2$ when combined with the carbon isotope measurements would provide new insight into the sublimation and condensation of $CO_2$ in polar regions.

***Measurement Goals:*** To address these goals, spatially resolved profiles of the isotopologues of the major and minor gases are needed. Precision requirements depend on the isotope. Deuterium content of water must be measured with at least 5% precision and 10% accuracy, while the carbon and oxygen isotopes of $CO_2$ and CO must be measured with 0.5% precision and 2% accuracy. Isotopic abundances need to be measured over the lowest 20 km of the atmosphere (or 40 km for deuterium) with a vertical resolution of 5 km.

## Trace Gas Inventory

Primary measurement requirements for MSO trace gases are summarized in Table 1. The desired sensitivities reflect science objectives that may be attained by a combination of infrared and sub-millimeter (or millimeter) spectral approaches. In general, optimum trace gas detections (methane and isotope ratios) are best supported by infrared solar occultation spectroscopy. Mapping dust and ice aerosol measurements would be best supported by passive infrared limb radiometry or spectroscopy. Optimum mapping and vertical coverage of photochemical species, including aerosol-independent sensitivity below 20 km altitudes, would be best supported by passive sub-millimeter limb spectroscopy. Global mapping of species would provide latitudinal-longitudinal-temporal coverage and resolution sufficient to resolve the key spatial and temporal correlations among the photochemical, aerosol and surface/sub-surface constituents of the Mars atmosphere.

***Measurement Goals:*** Very little is known about the trace gas composition of the Martian atmosphere. Generally, previous attempts to quantify many compounds of interest for studies of photochemistry and surface exchange have been unsuccessful and yielded only very high upper limits. Earth's atmosphere contains many of these compounds due to the existence of biology and volcanism. The table below lists a number of species that might possibly be detected. Given is the current upper limit from existing measurements along with the predicted abundance due only to gas phase photochemistry. A significant improvement in current knowledge would require a sensitivity of about 1–10 pptv.

| Molecule | Predicted Abundance due only to gas phase photochemistry (ppbv) | Upper Limit (ppbv) of Existing Measurements |
|---|---|---|
| $HO_2$ | ~1 | - |
| $NO_2$ | ~0.1 | 10 |
| $N_2O$ | ~0.001 | 7 |
| $C_2H_2$ | 0 | 2 |
| $C_2H_4$ | 0 | 500 |
| $C_2H_6$ | 0 | 400 |
| $H_2CO$ | 0 | 3 |
| HCN | 0 | - |
| $H_2S$ | 0 | 20 |
| OCS | 0 | 10 |
| $SO_2$ | 0 | 1 |
| HCl | 0 | 2 |

**Table 1**. Current upper limit and predicted abundances of a number of trace atmospheric species for Mars.

## 5.2 Atmospheric State

### Dynamics, Transport, and Winds

Measurements of atmospheric dynamics, winds, and transport would be a primary objective of the MSO mission. Mars is a very windy planet, owing fundamentally to its thin, mostly $CO_2$, atmosphere. Despite the low density of the atmosphere, the winds are strong enough to raise large amounts of dust from the surface. At times, the planet becomes almost completely enshrouded in a near-global veil of dust in the atmosphere. The atmospheric dust has an enormous impact on the thermal structure of the atmosphere and thus on the winds (and therefore on the dust raising itself) due to the fact that it strongly absorbs solar radiation and heats the thin atmosphere very strongly. The dust also produces strong effects via its interaction with IR radiation. The winds on Mars transport water vapor, water ice clouds, and $CO_2$ ice clouds, along with $CO_2$ itself to the condensing and subliming polar caps. The winds also transport and mix all of the minor atmospheric gaseous constituents (e.g., ozone, carbon monoxide, $H_2O_2$, etc.), and they are a primary player in all surface-atmosphere interactions and exchanges on the planet. If there are local and/or transient sources of gases such as methane and $SO_2$ on Mars, then the winds are critical in determining the distribution of these gases in the atmosphere. Finally, the winds are of crucial importance for spacecraft EDL on Mars.

Despite the huge importance of winds on Mars, at present there are remarkably very few direct observations of them. Only the Viking Landers and Mars Pathfinder have obtained in-situ wind measurements, at the surface. The only direct wind measurements above the surface have been made from the Earth, and both the spatial resolution and the accuracy (as well as the coverage) of these are very limited. Some winds have been derived from cloud tracking imagery, but these tend to be problematic – most strongly because of the difficulty of determining what altitudes they are relevant to. A primary objective of MSO would be to obtain good direct wind measurements for the first time, with both complete global and local time-of-day coverage, from near the surface to altitudes of ~80 km or more. When combined with good measurements of the atmospheric temperatures and the dust and water abundances this would enable, for the first time, a complete characterization of the general circulation of Mars. The latter is the central player in the climate of Mars, which is dominated by the global cycles of dust, water, and $CO_2$. Most importantly, wind measurements throughout the bulk of the lower atmosphere would enable the transport of atmospheric constituents to be directly investigated. This would enable the sources and sinks of these to be determined much better than has previously been possible. The wind measurements would also greatly enhance our ability to design and engineer spacecraft EDL, and other spacecraft maneuvers in the lower atmosphere (e.g., aerocapture). Ultimately, much better knowledge of the Mars winds would most certainly be required for human missions.

Mars atmospheric dynamics have many fundamental similarities to the Earth, as well as a number of major differences. Both planets are relatively small ones with shallow atmospheres that are strongly heated by the Sun. Both planets are rapidly rotating, such that the effects of the planetary rotation are of dominant importance for large-scale motions. Both planets have very similar obliquities at present. These very basic similarities lead to many similarities in the atmospheric dynamics, at both large and smaller scales. Mars has traveling mid-latitude weather systems fundamentally similar to those on Earth. Mars has forced quasi-stationary waves fundamentally similar to those on Earth. Mars has a Hadley cell circulation, which is of tremendous importance for the tropical and subtropical atmospheric circulation. There are also some very large differences between the two planets. Mars has no oceans that strongly buffer seasonal and diurnal temperature changes. One consequence of this is that the summer hemisphere atmospheric dynamics on Mars differs much more greatly from that in the winter hemisphere than it does on Earth. Mars has a very eccentric orbit, which plays a critical role in the "seasonality" on Mars. In particular, the dust storm season occurs during the portion of the annual cycle when Mars is closest to the Sun and the atmospheric heating is strongest. The thinness and $CO_2$ composition of the Mars atmosphere cause it to respond much more strongly to the diurnal solar forcing, such that Mars experiences very large thermal tides by comparison with Earth. The smaller size of Mars causes the Hadley cell to be much larger in planetary extent than on Earth; the stronger atmospheric heating causes it to be much stronger and thus much more effective in producing cross-equatorial transport. The Mars topography is huge and characterized by a unique hemispheric asymmetry. This plays a key role in causing the Hadley cell to be much stronger in southern summer than in northern summer, which has a crucial impact on the key climate cycles. The topography also is of critical importance for the weather systems in producing storm zones, and for the quasi-stationary waves that can produce regional climates. Finally, the lack of a tropopause and the lack of substantial ozone on Mars contribute to yield an essentially continuous lower atmosphere that essentially extends from the ground up to the homopause (~100 km).

While existing measurements of the Mars atmosphere from orbit have now enabled a first-order characterization of temperatures, dust, and water vapor, they have not enabled a characterization of winds and transport. Some indirect inference of winds from temperatures can be made, but this is generally much more difficult to do for Mars than for Earth because of the basic fact that motions are much less geostrophic on Mars (largely because Mars is a much windier planet). Direct measurements of winds from orbit would be required in order to determine the true global distribution of winds in the Mars atmosphere. Near-surface winds, which are absolutely critical for atmosphere-surface interactions, can only be determined by direct observations. The planetary-scale winds on Mars are considerably more two-dimensional than those in the Earth's atmosphere because of the very strong atmospheric heating and the much stronger Hadley cell. The best current Mars circulation models show that meridional jets exist in the Mars atmosphere under dusty conditions, with speeds of ~40–80 m/s and more. Thus two-dimensional (vector) measurements of the horizontal winds would be critically important, in general, for Mars. They are especially so in the context of north-south transport. Such measurements would also be required in order to define the traveling weather systems, the quasi-stationary waves, and the thermal tides, which all have strong zonal and meridional components. The characteristic vertical scale for many atmospheric motions is of the order of the pressure scale height, about 10 km for Mars. Many motions have larger vertical scales than this, but there are many examples of motions that have smaller vertical scales – e.g., gravity waves, slope winds, and western boundary currents. Thus the winds need to be measured with a minimum vertical resolution of ~10 km, but any possible improvement in this resolution is highly desirable. A vertical resolution of ~5 km would be much better than one of ~10 km, especially so in the context of transport. It would also be commensurate with the MSO measurements of temperatures, dust, and water. The MSO orbit, which would be high-inclination, essentially limits the longitudinal resolution of the wind measurements. At an altitude of ~300 km this means that there are about 13 orbits per sol, which limits the longitude resolution to ~30°. For large-scale circulations, this is not a primary limitation because of the fact that the major components of the general circulation are much closer to planetary scale than on Earth. Finally, the desired latitude resolution is ~5°; 10° is a minimum resolution. Extremely sharp latitudinal gradients of wind exist on Mars, especially in association with the winter polar vortexes, and in these regions even higher resolutions (~2–3° or better) are very desirable, at least at times. In the core of the polar vortexes the winds tend to be predominantly zonal, so the highest latitude-resolution wind measurements there could be one-dimensional and still be highly useful.

Transport is the movement of energy, momentum, and material both vertically and horizontally from place to place on the planet by atmospheric winds. The effects of such winds are reflected in atmospheric temperature structure, in the mass distributions of non-uniformly mixed gases, and in the structure and intensity of the wind field itself. The transports themselves are key to understanding the cycles of dust and water vapor and the redistribution of heat and momentum. Despite the short radiative time constant of the thin $CO_2$ Martian atmosphere, transports of heat and momentum are sufficient to affect the polar heat balance, the seasonal polar caps and their interannual variation. Furthermore, the transports of material from surface sources to atmospheric or surface sinks are important to explaining the distribution of water vapor and aerosol and potentially of regional sources of trace gases which have subsurface origins, either geochemical or biochemical in nature. Vertical mixing and transport in the atmosphere also affect photochemically important gases (e.g., CO).

In principle transports of energy, momentum or material can be derived from direct measurements of winds and of the transported quantity (e.g., temperature or water vapor). In practice, remote sensing techniques from orbital platforms have adequate temporal and spatial coverage to address directly only regional and global components of the transport and even then (and even for Earth) remotely sensed winds seldom have the precision to directly derive atmospheric transports. In part this is due to the fact that it is not just the flux of material or energy that is important, but its flux-divergence, which requires spatial derivatives that tend to amplify measurement noise and error.

Thus, the determination of transport and its inverse, in which trace species are tracked back to their sources, is done using atmospheric circulation models. One approach is to validate the model predictions by comparison with observed winds and with the transported trace gases themselves. This requires having a good description of atmospheric heating which for Mars depends upon the distributions of dust and ice, surface albedo and thermal inertia. A second approach is to use methods of data assimilation in which a blend of model predictions and direct observations is produced, essentially applying systematic corrections to the model predictions as a function of time. Data assimilation methods have the advantage that the modeled quantities can be analyzed more objectively (than trial and error methods) to diagnose both the model limitations and observational systematic errors.

In either case, whether using assimilation or simulation alone, the analysis works best when a suite of tracers with different life cycles and spatial variations is used. Gases with lifetimes of months to a few years are most diagnostic; shorter lifetimes will localize the tracer, while long lifetimes will produce uniformly mixed distributions that are no longer independent. One exception to the latter is that non-condensable inert gases (e.g., argon or CO) can reveal seasonal transport given the massive condensation/sublimation of up to 30% of the Martian atmosphere in the polar regions. For transport purposes, water vapor, carbon dioxide, ozone, methane and their isotopes, together with some shorter lived, higher order hydrocarbons, can provide the variety of trace gases needed to test and improve model predictions and our basic understanding of the physical processes involved in their origin, loss and transport.

The value of wind measurements should not be underestimated in this analysis of transport and the ability to define surface (and thus subsurface) sources and sinks. While temperature measurements alone provide powerful constraints on model simulations, particularly when coupled with observations of aerosol loading, the system is not wholly constrained without the additional observations of winds and/or pressure.

***Measurement Goals:*** The baseline set of wind measurement objectives for MSO would be composed of two-dimensional (vector) horizontal winds, observed over the whole globe each sol, on both the day and night sides. The minimum precision that is needed is ~10 meters/sec, but the goal is ~5 meters/sec over at least a good portion of the lower atmosphere. The minimum vertical resolution for the wind measurements is ~10 km, but doing better than this is an extremely important goal. The minimum latitude resolution of the wind measurements is ~10°, but a resolution of ~5° is much better. Even higher latitudinal resolutions are very desirable at least at times, in certain regions of the planet (e.g., the winter polar vortexes). The wind measurements need to be obtained throughout the lower atmosphere, extending from within the lowest scale height to ~80 km. Even higher altitude measurements would be very valuable, especially in relation

to the Mars Scout aeronomy mission proposed for launch in 2011. Good wind measurements in the lowest scale height would be very valuable for the scientific objectives of the MSO Mission, but it is recognized that these would be difficult to obtain. It is fully recognized that a wind instrument would have to make a number of trade-offs between the various measurement specifications (e.g., precision, vertical resolution, and latitudinal resolution) in order to be feasible in the basic contexts of cost, volume, power, and schedule. A wind instrument that would be flexible enough to allow some of these trade-offs to be made during the mission (and even changed from sol to sol) is viewed as distinctly advantageous.

An understanding of transport and the ability to invert tracer distributions to define regional sources and sinks (including photochemical loss higher in the atmosphere) essentially requires the same wind, temperature and opacity measurements as described previously plus observations of the time-varying concentrations of trace gases (including water vapor). Optimally, a suite of trace gases having a range of lifetimes and/or spatially varying sources should be measured. Requirements include planetary-scale coverage throughout at least one Martian year and preferably for several diurnal cycles. Measuring both horizontal components of the wind is much preferred. Various combinations of precision and vertical resolution of the wind components could produce comparable results, but terrestrial experience has shown that the value of wind measurements on model simulations and transport inversion is significantly greater when the vertical resolution of wind observations is comparable to an atmospheric scale height or better and the latitude resolution is 10° or better, particularly in the vicinity of the stronger jets.

## Climate Characterization

An initial assessment of the current Martian climatology has been obtained by data returned from Viking, Mars Global Surveyor (MGS), Mars Odyssey, Mars Express, and Mars Reconnaissance Orbiter (MRO). The key atmospheric state parameters observed to date have been the atmospheric temperature profile as a function of height, the column-integrated optical depth of dust and water ice aerosol, and the column abundance of water vapor. These observations show a distinct and generally repeatable dependence on season, latitude, and longitude, although significant variations from one Martian year to the next are also observed, most notably associated with the intermittent occurrence of global-scale dust storm events.

Martian seasons are generally similar to those of Earth because of the similar obliquities of the two planets. Differences between Martian seasons are more extreme, however, because of the lack of moderating oceans and because of the large Martian orbital eccentricity. Mars' perihelion is currently near southern summer solstice; this, coupled with inter-hemispheric topography differences, enhances the differences in climate between the two hemispheres. TES on MGS created an invaluable dataset showing geographical and seasonal variations in dust, temperature, clouds and water vapor for three Mars years. MOC wide-angle daily global maps in red and blue wavelengths left a similar legacy in the visible portion of the spectrum for four Mars years, and MARCI on MRO is adding to this continuous record. Although many of the weather phenomena observed are fairly repeatable from year to year, there are notable exceptions – especially for the dust cycle. An early dust storm, similar to the first 1977 Viking storm, was observed in Mars Year (MY) 25 (2001), and a perihelic storm similar to the second 1977 Viking storm was observed in the most recent year (2007, MY 28). There were no such "global-scale events" in MY 24, 26, or 27.

Large regional storms moved from the northern hemisphere to the South Pole in MY 26 and MY 27. Although valuable data on these events have been obtained by MGS and MRO, the reasons for the large interannual variations in dust activity are still obscure. They may be related to changes in surface albedo due to deposition and removal of dust that can be monitored by a wide-angle camera similar to MOC and MARCI.

The inter-hemispheric asymmetry extends to the Martian water cycle: the northern hemisphere is moister than the southern hemisphere. This is partly related to the fact that the perennial north polar cap is a major source for atmospheric vapor, but asymmetric transport of the vapor also plays a major role. The aphelion cloud belt that forms in the ascending branch of the Hadley Cell during northern summer appears to act as a block, preventing the transport of water to the southern hemisphere. No such impediment exists to transfer in the opposite direction during southern spring and summer, and so there is in effect a pump moving water from south to north at this time.

Although much progress has been made, knowledge of the current climatology is limited by lack of observations in several key areas. Most importantly, there are currently no missions planned after Mars Express and MRO capable of global-scale monitoring of the atmospheric state. This is a serious shortfall. A long baseline of observations is crucial to understanding the current climate and the physical mechanisms that govern it, both to be able to model past climates, and to successfully predict the current atmospheric state for future robotic and manned landings. Given that global-scale dust storm events occur intermittently only about once every three martian years, it is likely that at least ten Mars years of observations would be needed to adequately define the variability associated with that important process. A continuous record of at least that length would be preferred to better understand the feedbacks and cause-and-effect relations between processes on seasonal and year-to-year time scales, but minimizing the gap in observations after MRO and Mars Express is the next best option. Therefore, it is important to include atmospheric monitoring on MSO, which represents the next possible chance for such observations.

Other aspects of the current climate not well sampled so far by observations are diurnal variations (for example, both MGS and MRO observe only afternoon and early morning local time), direct measurements of wind velocity, and the vertical distribution of aerosols and water vapor. Full coverage of the diurnal cycle would greatly help the identification of wavemodes and the modeling of the water cycle including condensate clouds. The addition of wind observations would be an essentially new observation that would provide important new constraints for circulation models. Information on the vertical distribution of aerosols would greatly improve both the modeling of heating rates and the knowledge of circulation patterns through tracer motions.

*Measurement Goals:* The most important observations to make for climate monitoring are:

- Atmospheric temperature
- Optical depth of dust and water ice aerosols
- Wind velocity
- Water vapor abundance
- Surface pressure, temperature, and albedo

Each of the above quantities (except for the surface values) should be determined as a function of height with a vertical resolution of at least a pressure scale height (10 km minimum, 5 km preferred) over a broad vertical range (from the surface to at least 60 km). The desired spatial coverage and resolution is driven by the size and extent of features important to climate characterization. Global coverage, obtained with near-continuous (~85% or better) observations at least every 5°–10° of latitude along the orbit track is required so that phenomena such as regional-scale dust storms and the polar vortex are adequately resolved. Climate phenomena change on time scales ranging from a day or less (e.g. waves, evolution of dust storms) to seasonal (e.g. formation and decay of polar hoods and aphelion season water ice cloud belt), to interannual (e.g. occurrence of global-scale dust storm events and redistribution of surface dust). Therefore, observations with global coverage should be taken on a nearly daily basis for at least one Martian year, and preferably for several Martian years.

## Mesoscale Atmospheric Processes

Observations of Martian atmospheric phenomena at the mesoscale level (i.e., from several to hundreds of kilometers) were first obtained by the camera systems onboard the Mariner 9 orbiter. Although the Viking orbiter cameras expanded significantly upon both the number of observations and the scope of phenomena imaged, it was only with the arrival of MGS that such data were obtained with both global and systematic coverage. Through the use of discrete dust and water ice aerosol clouds (or lack thereof) and their subsequent evolution, researchers have been able to examine a range of mesoscale processes that include frontal systems, transient eddies, boundary layer stresses, volatile transport, and aerosol microphysics. Although such studies have revealed repeatability for some of the observed phenomena (e.g., cross-equatorial storms, polar storm fronts), significant spatial and interannual variability is also seen. This includes the poorly understood transition of common localized lifting of dust to the less frequent global-scale events.

Despite the insight provided by the MGS record from 1997 through 2006, a longer temporal baseline is critical for further characterizing the annual and the interannual behavior of mesoscale processes in the Martian atmosphere. Fortunately, the Mars Reconnaissance Orbiter (MRO) has been able to fill the void left by MGS in terms of instrument capability and coverage. However, the unexpected loss of MGS raises the possibility of a lack of observing capability in the post-MRO era. Neither the other current missions (Mars Odyssey, Mars Express) nor those planned (Mars Scout 2011) possesses the same capability for global monitoring. A gap in the continuous record will have the particular consequence of greatly hampering efforts to study the interannual variability of processes that only occur ever few years, such as the aforementioned development of global dust events. As a result, MSO would offer the first and best opportunity to continue the observational record of atmospheric mesoscale processes.

A missing facet of mesoscale studies enabled by MGS and MRO global observations is that of diurnal variations; the orbits of MGS and MRO allow for the (nadir) viewing of only two local times. Because a variety of mesoscale phenomena are sensitive to time-of-day effects (e.g., solar insolation, downwelling radiance, and abundance of water vapor), the ability of MSO to sample the diurnal cycle would offer a significant enhancement to the MGS-MRO record by adding another dimension of information. In addition, the value of diurnal coverage by MSO would be greatly amplified by any overlap in operations with MRO. By providing direct comparison of the same

location within the same Martian day (as opposed to doing so on a climatological basis), one could much better isolate the diurnal variation of the observed phenomena (e.g., dust lifting center, eddy activity) from the sol-to-sol evolution.

***Measurement Goals:*** The key aspects of the MGS-MRO atmospheric mesoscale observations that should be included in an MSO capability are:

- Ability to observe continuously
- Limb-to-limb coverage with a resolution of ~1–2 km at nadir (5–10 km on the limb)
- Ability to discriminate between condensate and dust aerosols

The above requirements would produce a global map of Mars, and limb observations at 26 longitudes every day.

## 5.3 Surface Change Science

The surface science objectives of the MSO mission are focused on the surface properties and morphologies associated with surface-atmosphere interactions and surface change. Experience has shown that these changes occur on both local and regional scales, and can occur on intermittent, seasonal, and year-to-year time scales. Some of the most dynamic changes occur in the polar regions, but numerous changes occur in the equatorial and mid-latitudes, associated with aeolian, mass wasting, impact, and possibly, volatile release, activity.

### Regional and Local Changes

A variety of changes have been observed that involve process occurring at regional scales. The most conspicuous of these are widespread albedo changes associated with regional and global dust storms. These albedo changes are caused by the deposition and removal of thin layers of surface dust. This process can, however, have significant implications for the long-term evolution of the Martian surface, acting as the major element of contemporary erosion and geologic change. Observed changes in surface albedo also provide the best indication of Martian wind transport on a global scale. These changes directly influence surface temperatures, which in turn influence the global circulation. Wind stress is enhanced in darkened areas and decreased in brightened areas, which can produce a positive feedback mechanism by which the albedo changes strengthen the winds that generate the changes. Recent models predict a year-to-year global change in surface air temperatures as a result of these changes in surface heating that may play an important role in climate fluctuations on yearly, decadal, or longer timescales.

A variety of small (10's to 100's of meter)-scale features, including dust devil tracks and slope streaks, exhibit regional differences in their spatial occurrence and temporal variability. These features are readily observed at 2–5 meters/pixel resolution, and their occurrence has been well documented using MOC imaging. Convective vortices - dust devils – may form an important component of the dust lifting processes on Mars. These features have high tangential winds and strong vertical velocities, and are very efficient at lifting dust from the surface and raising it to high altitudes. This process is less size-dependent than near-surface wind stress lifting. Dust devil tracks provide an excellent means of observing the surface-atmosphere interface across the planet. Dust

devils may play an important role in lifting surface dust and raising the global opacity, which can then lead to enhanced global heating and wind velocities, which may then trigger regional dust lifting, leading to large-scale dust storms. Dust devils may also be an important component of the long-term global dust cycle, acting to lift dust and prevent its long-term accumulation. Previous mapping has demonstrated that dust devils, as observed through imaging of dust devil tracks, vary in occurrence on both seasonal and year-to-year timescales. A long-term record of these features, acquired through meter-scale imaging, is critical to developing models of the current climate and its interannual variability.

Slope streaks on Mars are a class of active surface process that were first observed by the Viking Orbiters, and have been shown to have wide distributions using MOC imaging. These features are 10's to 100's of meters wide and are strongly correlated with regions of low thermal inertia. Two types of models have been suggested: dry mass movement in the form of dust avalanches and wet liquid flow that transports or stains the surface material. Recent HiRISE imaging shows that these features transport significant amounts of materials, with some having meter-thick deposits, and are often associated with localized disturbances (i.e. rock falls). Long-term observations of these active features would provide a means of studying active processes on Mars, and determining the nature of the role of volatiles in this activity.

A final example of small-scale processes that occur on regional and global scales is the formation of small impact craters over time. The current impact flux has been observed using MOC high-resolution and wide-angle images, which revealed the formation of 20 new impact craters 2 to 150 meters in diameter that formed during the decade of MGS observations. The impact flux rate is currently only weakly constrained by the MOC data; MRO CTX and MARCI observations will extend this record, but the capability for a decade-long survey of impacts from wide-angle imaging, together with the ability to inspect the morphology of these fresh craters at meter-scales, would significantly improve the statistical determination of the current crater flux. Of particular interest would be the formation of modest sized (5–50 m diameter) craters in the mid- and high-latitude regions to use as probes into the martian sub-surface in regions of potential near-surface ground ice.

In addition to small-scale features that occur on regional scales, a variety of small features are of interest in determining the nature of the current Martian surface and the role of volatiles in highly localized environments. Examples of these features include gullies, with the potential for isolated, current activity, avalanches and rock falls, and dune motions. These processes occur very infrequently or at rates that require long-term monitoring at meter-scales to detect changes at the expected rate of motion on Mars. When these changes occur however, they have been observed, or are expected, to occur at spatial scales of meters to tens of meters, allowing their occurrence to be detected and studied with meter-scale imaging. While rare, the occurrence of these changes is critical to our understanding of the occurrence and magnitude of volatile release from the sub-surface and the current rate of surface evolution. For example, repeated MOC imaging of young gully features revealed the occurrence of several cases where changes, potentially due to the release of volatiles, were detected of the course of several years. Several models have been proposed for gully formation, including discharge of liquid water from sub-surface aquifers, the melting of pore ice that diffused inward from the atmosphere during periods of colder temperatures, or melting of a snow layer deposited during periods of higher obliquity when surface ice was stable at these latitudes are the most plausible. Long-term monitoring of gullies is a high-priority for determining their current activity and for testing these models of gully formation.

A wide range of surface morphologies have been observed with meter-scale imaging, including intracrater and polar layered deposits, fluvial features ranging from chaotic outflows, streamlined islands, eroded terraces, to deltaic deposits, mid-latitude mantles and morphologies potentially related to glacial process, and a full range of aeolian features. MOC imaged approximately 5% of the surface at 3–6 m/pixel resolution. The MRO HiRISE will image far less. Clearly, a vast fraction of Mars remains to be observed at meter-scale resolution. Given the suite of discoveries made to date by MOC and HiRISE, it is likely that additional discoveries and insights would be obtained from meter-scale imaging of the remainder of Mars.

*Measurement Goals:* For the observation of albedo changes, wide-angle imaging at 50–100 meters/pixel is required along with calibrated broadband solar reflectance from multiple emission angles to separate surface and atmospheric components. For the observation of morphology changes, the scale of features to be observed is typically 5–100 meters for gullies, layers, slope streaks, dust devil tracks, and small impact craters. These features could be detected and their occurrence and distribution mapped using imaging at 1 meter/pixel.

## Polar Regions

The polar regions of planets are especially sensitive to processes that modify climate patterns because of the strong seasonal modulation of insolation in those areas. For example, the effects of global warming on Earth are strongest in the polar-regions. Following discovery of layered terrains in the Martian polar-regions by space missions in the 1970s the principal conjecture concerning their significance is that they are associated with changes in climate induced by astronomically induced changes in orbital parameters. Perturbations of Mars' orbit by the gravitational forces from other planets cause the inclination of its rotational axis, the eccentricity of its orbit, and the longitude of perihelion to vary with periods of tens of thousands to millions of years. These in turn affect the distribution of insolation on the planet. The effects are largest at the poles where phase changes occur, and the Martian volatile cycles therefore respond strongly. In particular, the near vicinities of the two perennial caps – the portions of the caps that survive their respective summer seasons – contain clues as to climate variations on Mars.

The region surrounding the north polar perennial cap is of special interest because this cap is a major source of atmospheric water on Mars at the present time. It is presumed that the layers that underlie the perennial cap consist of mixtures of water ice with varying amounts of dust or sand that were deposited in the past during favorable combinations of orbital parameters. However, it is difficult to extrapolate to previous combinations of orbital parameters until the processes that are currently active are fully understood. The mass balance of the perennial north polar cap (i.e. whether it is gaining or losing water currently) has still not been definitively determined from the data that are currently available. Profiles of wind speed and water vapor concentration as functions of latitude and altitude would help resolve the issue by allowing estimates of the flux of water returned to the cap in late summer and autumn. Circulation models that are constrained by observations of the current north perennial cap water cycle could then be used with other combinations of orbital parameters to extrapolate the Martian water cycle to past and future climates.

The south perennial cap unlike its northern counterpart consists of a veneer of $CO_2$ ice perhaps 10–20 meters thick set on a basement that consists mostly of water ice. The residual cap $CO_2$ ice remains relatively dust free through the summer, and the resulting high albedo prevents its sublimation. The frost surface in the south cap consists of a bewildering range of morphologies (popularly referred to as "Swiss cheese") including often-complex collapse features surrounded by flat mesas as well as complex ridges and valleys resembling fingerprints. Up to six individual layers can be identified in the various structures. Observations from MY 24–27 reveal that the pits grew larger during the four-MY MGS mission. For a large subclass of the features the rate of increase in diameter is about 4 meters / pixel / MY, requiring a minimum resolution of 2 meters / pixel for measurement. These results indicate that there are components to the $CO_2$ cycle that have periods of decades or centuries and suggest that there is a net transfer of $CO_2$ from the Residual South Polar Cap to the atmosphere averaged over the year.

There is strong evidence that we have not just happened to observe the residual south cap at the exact time of its disappearance. Comparisons of images of the residual cap obtained by Mariner 9 (MY 10) and MGS (MY 24) clearly show that a significant area that is currently covered with residual $CO_2$ frost was unfrosted in the former year. Therefore some process, currently unknown, led to net deposition of $CO_2$. Taken together, the current erosion of the "Swiss cheese" mentioned earlier and the net deposition of frost in the past suggest a component of climate change with a time scale of decades that is not understood. This cycle has strong implications for the Martian water cycle because exposure and sublimation of the water ice beneath an area from which $CO_2$ frost has been removed could be an important factor. Deciphering these clues would require continuous monitoring of the residual south cap for decades both at high resolution (>2 meters/pixel) and lower resolution (> 500 meters/pixel).

***Measurement Goals:*** High-resolution imaging of the residual polar caps at 2 meters per pixel or better is required. This could be accomplished with an imager with 1 meter per pixel resolution if the air mass to the pole is 2. Wide-angle imaging of the residual caps at resolution of 500 meters per pixel with a minimum of red and blue filters is also desired for monitoring larger areas.

## 5.4  Summary of Science Measurement Goals

Below is a summary of the measurement goals for all quantities as recommended by the SDT.

| **Photochemistry** | | | |
|---|---|---|---|
| *Quantity* | *Sensitivity* | *Vertical range* | *Vertical resolution* |
| $H_2O$ | 10 ppbv | 0–60 km | 5 km |
| $H_2O_2$ | 100 pptv | 0–40 km | 5 km |
| CO | 1 ppmv | 0–60 km | 5 km |
| $O_3$ | 1 ppbv | 0–40 km | 5 km |
| | | | |
| **Isotopic Measurements** | | | |
| *Quantity* | *Sensitivity* | *Vertical range* | *Vertical resolution* |

| D/H (in $H_2O$) | 5% precision, 10% accuracy | 0–40 km | 5 km |
|---|---|---|---|
| $^{13}C/^{14}C$ (in $CO_2$) | 0.5% precision, 2% accuracy | 0–20 km | 5 km |
| $^{16}O/^{18}O$ (in $CO_2$, $H_2O$) | 0.5% precision, 2% accuracy | 0–20 km | 5 km |
| $^{17}O/^{18}O$ (in $CO_2$, $H_2O$) | 0.5% precision, 2% accuracy | 0–20 km | 5 km |
| | | | |
| **Trace Gases** | | | |
| *Quantity* | *Sensitivity* | *Vertical range* | *Vertical resolution* |
| Methane | 50 pptv | 0–60 km | 5 km |
| Other species | 1 pptv | —— | —— |
| | | | |
| **Atmospheric State** | | | |
| *Quantity* | *Sensitivity* | *Vertical range* | *Vertical resolution* |
| Temperature | 2 K precision, 2 K accuracy | 0–80 km | 5 km |
| Wind Velocity (2-D) | 10 m/sec precision | 5–80 km | 10 km |
| Aerosol Optical Depth (dust and water ice) | 0.05 precision at visible wavelength | 0–60 km | 5 km |
| Water Vapor | 10% precision, 10% accuracy | 0–60 km | 5 km |
| | | | |
| **Surface Properties** | | | |
| *Quantity* | *Sensitivity* | *Vertical range* | *Vertical resolution* |
| Surface Temperature | 1 K precision (at 240 K) | —— | —— |
| Solar-band integrated albedo | 5% precision | —— | —— |

**Table 2**. Recommended measurement goals for MSO.


In addition to the above, mapped quantities should be obtained with at least 90% coverage along the orbit track, amounting to at least every 5° of latitude along-track. Mapped quantities include all photochemical products, methane, atmospheric state quantities, and surface properties.

Imaging capability should include a high-resolution camera with 1 meter per pixel resolution and a wide-angle camera with 500 meters per pixel resolution and at least red and blue color channels.

# 6.  MSO MISSION IMPLEMENTATION

## 6.1  Sample Payload

In order to gain an understanding of the technical and resource requirements of MSO, the MSO team has been working with a set of strawman instruments that represent one possible response to the Plan A requirements detailed by the MEPAG SAG-2 report. This strawman payload, based on capabilities demonstrated either at Mars or in studies of the Earth's upper atmosphere, is comprised of five instruments:

**Solar Occultation FTIR spectrometer**
A solar occultation FTIR spectrometer would characterize the composition of the Martian atmosphere from the surface to an altitude of 100 km.  The global coverage of this instrument is controlled by the inclination of the spacecraft orbit.  As the inclination increases poleward of 74º, frequency of sampling, particularly at low and mid latitudes, is compromised.  The orbit trades have been studied by the project and are discussed below. The utility of combining a bright source and very high spectral resolution for surveying atmospheric trace gases is well demonstrated in observations of the upper atmosphere of Earth

**Sub-millimeter spectrometer**
A sub-millimeter spectrometer would have a dual purpose: 1) Determine the wind velocity by measuring the Doppler shift of spectral features along the line of sight to the limb, and 2) It would measure the concentrations, locations and dispersal characteristics of specific atmospheric signatures, including water, as well as the temperature distribution of the atmosphere.  The global atmosphere would be sampled on a daily basis, through several seasonal cycles.  Observations over at least 1 Mars year are required to enable the diurnal and seasonal cycles to be distinguished.

**Wide-angle camera (MRO/MARCI-like)**
The wide-angle camera would provide daily global monitoring of the distribution of atmospheric dust and ices, together with surveys of the surface albedo. This would continue the synoptic monitoring of the surface and atmosphere carried out by MGS and MRO.

**Thermal IR spectrometer system**
A visual/infrared spectrometer with moderate spectral resolution would provide daily global measurements of the atmospheric dust and ices for correlation with the species and temperature measurements from the sub-millimeter spectrometer. This instrument would also carry out mineralogical studies and provide inputs for global atmospheric simulation models.

**High-resolution camera (HiRISE-class or TBD)**
A camera system with similar capability and mass to the MRO-HiRISE instrument, would provide additional surface coverage beyond that achievable with MRO, and allow for continued and longer-term monitoring of active processes. A HiRISE-class (sub-meter resolution) imager is desired for the continued certification (beyond MRO) of future landing sites.

## 6.2  Mission and Spacecraft Design

The MSO mission would be a 10 Earth year on-orbit mission. After a nine-month cruise, MSO would be propulsively inserted into a 1-sol Mars orbit and then aerobrake for approximately 6 to 9 months, followed by about 1 month of spacecraft and instrument commissioning. Accelerometer measurements made during aerobraking would complement the characterization of upper atmospheric structure carried out by previous Mars orbiters (MGS, ODY, MRO) during their aerobraking phases and, most likely, of the high-altitude observations by a still operating Mars Scout aeronomy mission.  Observations by the 2011 Mars Scout would aid the monitoring of the Mars atmosphere during the MSO aerobraking phase, which occurs during that part of the Mars year when great dust storms can occur, increasing densities at aerobraking altitudes (> 100 km).

MSO would enter a circular orbit of approximately 300 km altitude and 82.5° inclination, and spend approximately 1 Mars year in a Science Emphasis phase, before increasing its altitude to approximately 400 km.  It would stay in this higher (circular) orbit for the next seven Earth years, in a Telecom Emphasis phase.  Atmospheric science and landing site selection observations would continue throughout this latter phase, but with potentially lesser frequency than in the science phase.  MSO could provide relay to a 2013 lander, e.g. EXOMARS (ESA), and 2016 lander/orbiter (NASA and/or ESA - tentative).  The mission timeline (Figure 1) depicts the key mission events.
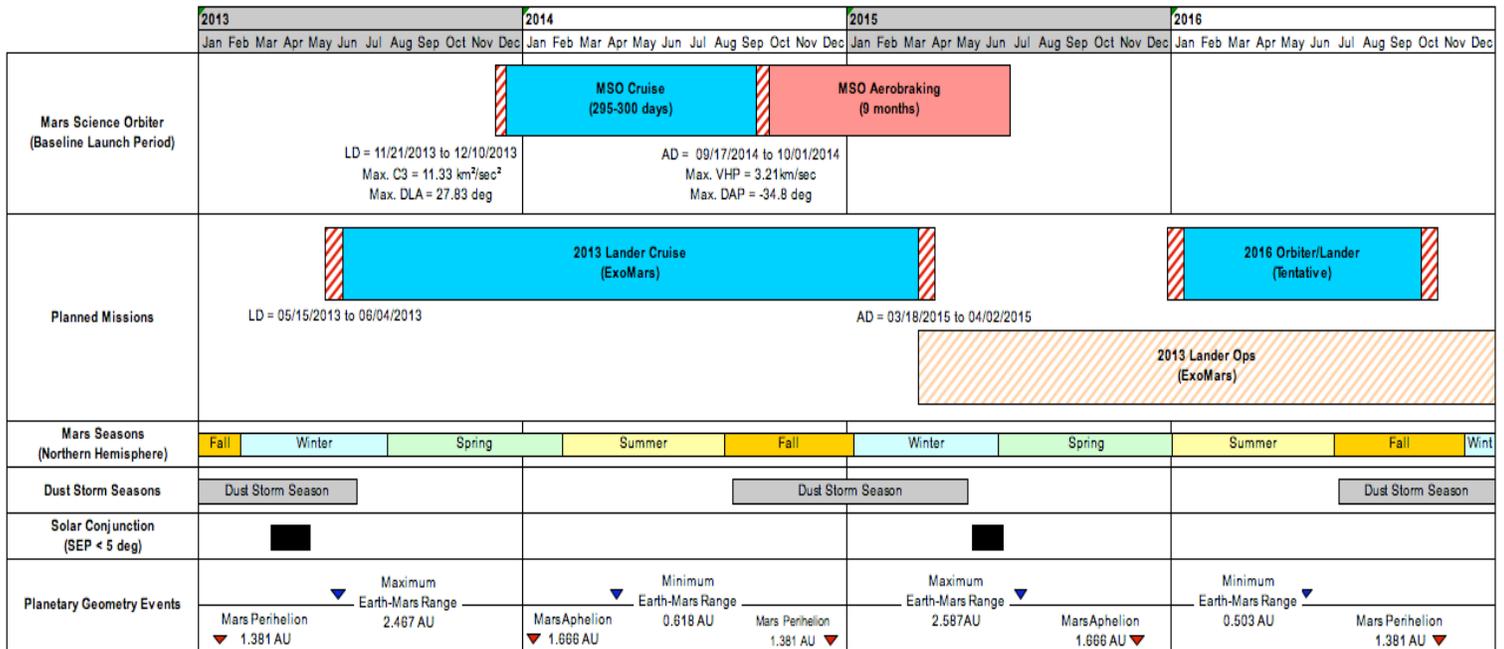


**Figure 1:** MSO Mission Timeline, depicting the key geometric events and other missions expected to be present at Mars during MSO's operational time frame.

## Orbit Tradeoffs

Orbit selection is driven by a combination of science and relay communication requirements. Like MRO, science data would be preferentially taken from a low altitude. At 300 km, a near-circular orbit results in approximately 13 revolutions per Earth day. The high-resolution camera and the FTIR trace gas instrument prefer significantly different orbit inclinations. In order to allow the camera to have global access and to have robust relay capability and adequate critical event coverage, high (high-inclination) inclinations are desired. On the other hand, the FTIR collects its best results, with most comprehensive latitude coverage, at 74°. An orbit trade study was performed to ensure the primary objectives of both could be met. It was concluded that the optimal orbit inclination to satisfy all mission requirements would be 82.5°. The selected orbit, which is a non-Sun-synchronous walking orbit, would have several advantages for science gathering, but has some impacts on the flight system design. These consist of:

- To obtain optimized high-resolution camera coverage, the orbit need only be slightly adjusted in altitude to achieve the required overlaps of swaths for mapping extended regions (Figure 2).

- The orbit enables the trace gas and atmospheric state instruments to view a full diurnal cycle each season, including solar occultations as needed, over a wide range of latitudes in multiple Mars seasons (Figure 3).

- However, the continuously varying solar beta angle of the orbit (Figure 4) becomes a significant driver for the mounting of the instruments, the trace gas instrument radiator design and placement, and the operational scenarios.

After one Mars year, the orbit would be boosted to a near 400 km altitude for the relay Telecom Emphasis phase. In this orbit, the camera's spatial resolution is slightly reduced and the trace gas observations are marginally degraded. However, this phase constitutes an additional seven Earth years of observing opportunity, extending the mission to almost a full solar cycle, so the cumulative science return is expected to be significant. The telecommunications orbit also meets the safe orbit requirement for planetary protection considerations.
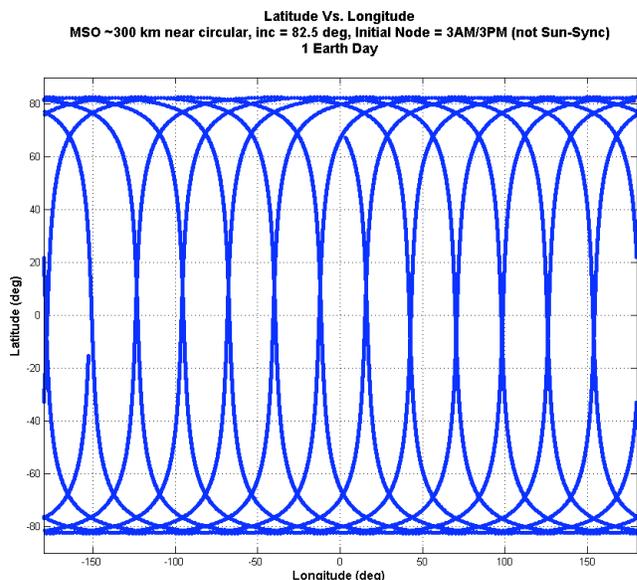


**Figure 2:** The MSO ground tracks during 1 Earth day for a near-circular orbit at ~ 300km, inclination = 82.5° and initial node = 3AM/3PM, (not Sun-synchronous). Each day accommodates approximately 13 revolutions.
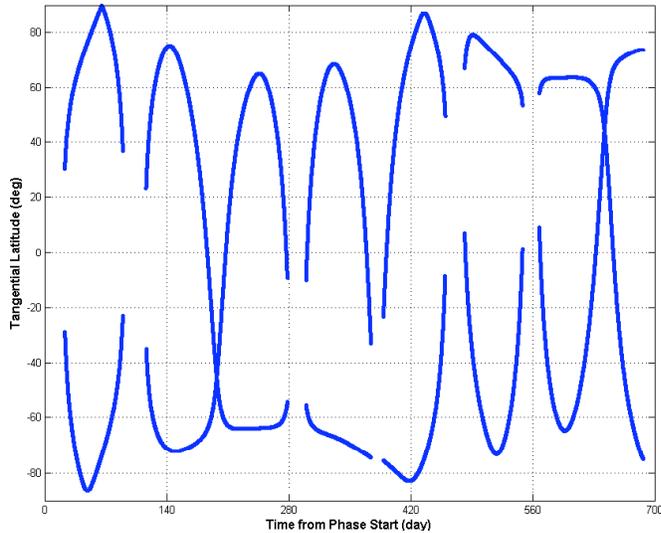
**Figure 3:** Depicts the FTIR instrument latitude access from a 273x327 km orbit, 82.5° inclination over one Martian year.
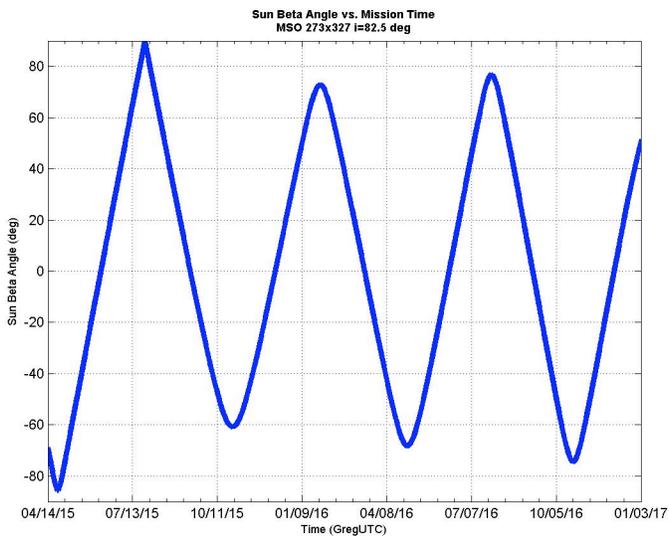


**Figure 4:** The solar beta angle versus mission time for an MSO at 273x327 km orbit and 82.5° inclination

## Instrument Accommodation

The MSO Project continues to investigate several approaches to accommodate the strawman payload. One promising configuration is described here.

The spacecraft would nominally maintain pointing with a fixed orientation relative to both nadir and the velocity vector, or ground-track. This pointing strategy results in widely varying Sun positions and any solar occultation experiment would have to be mounted on a two-axis gimbal in

order to align with the Sun. If the payload requires a cold, passive radiator, then the spacecraft would need to change its flight direction (alternating between flying forward and flying backwards) on a seasonal basis in order to keep the Sun off the radiator. Nadir pointing instruments such as the cameras would need to be able to handle flying in both directions.

High-resolution imaging would require the spacecraft to temporarily roll off-nadir, as the MRO has been doing routinely during its primary science phase.

The spacecraft would include 2-axis gimbaled solar arrays and a 2-axis gimbaled high-gain antenna. Earth communications would be nominally carried out on a non-interference basis with science observations.

The instruments would be mounted to the sides of the spacecraft, distributed around the circumference of a cylindrical structure.

## Observing Environment

(1) Trace gas observations require a quiet spacecraft. It is anticipated that articulations or mechanical actions on the spacecraft may introduce vibrations and therefore may not be permitted during occultation measurements.
(2) The trace gas experiment requires cooling. The passive thermal radiator assumed in the MSO configuration would prohibit viewing by this radiator of the Sun, Mars or any spacecraft surface. In this concept, the instrument should be gimbaled to align with the Sun during occultation measurements and to keep the radiator pointing towards the cold sky.
(3) High-resolution imaging also requires a quiet spacecraft as well as alignment of the camera with the ground-track to allow push-broom images.
(4) To accommodate these very different viewing requirements, instrument operations would be time-multiplexed.
(5) The wind instrument requires the spacecraft to keep a constant position angle with respect to the velocity vector and the limb during its observation.

## Schedule

The proposed MSO development schedule is shown below (Figure 5). The development phase durations and associated products are based on NASA project management requirements and lessons learned from recent planetary missions. Early schedule milestones include the Instrument Announcement of Opportunity release in early 2008 and the Mission Concept Review by the Fall of 2008.
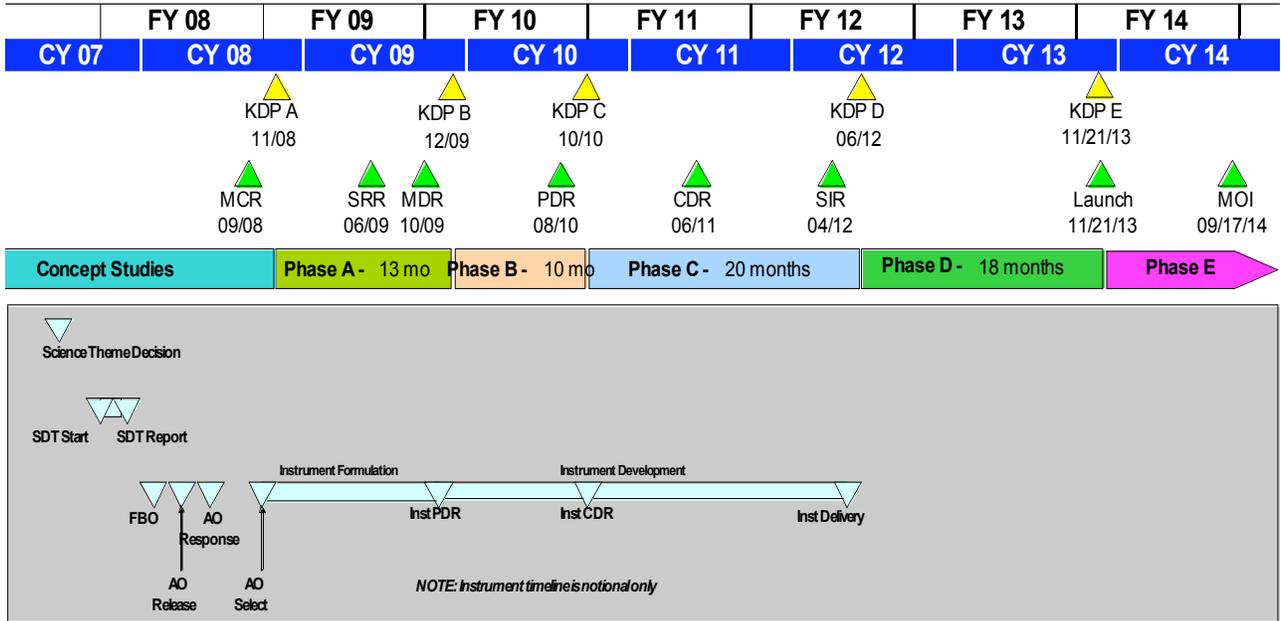
**Figure 5. Proposed** MSO development schedule.

# 7.  ISSUES AND CONCERNS

## 7.1  Scope and Payload Affordability

The SDT was told by the MSO Project that the main constraint on the payload was not mass or power, but cost of the payload.  The instrumentation and subsystems that would be required to carry out the five major objectives of MSO (atmospheric composition, atmospheric state, surface change, landing site certification, and telecommunications) is significant in scope and requires use in some cases of newly developed technology, with the need for increased reserves. The MSO SAG-2 had also noted that the desired (called core) payload was beyond the guidelines that had been provided to the project. There was hope that a contributed instrument would enable all key instruments to be accommodated. Certainly, there are international partners who have the technology to contribute key instruments to MSO, including any of the three major instruments identified below. While the SDT hopes that NASA would seek out and pursue contributions to the payload from potential partners worldwide, the SDT was uncomfortable relying on the hope that such a contribution would materialize. In addition, there was some concern that the temptation to invite participation on a noncompetitive basis might lead to an instrument that did not have the required measurement capabilities. Thus the SDT recommends that the required capabilities for the core payload are well specified, and that all instrument proposals, including proposed contributions, are competitively evaluated.

Three instruments tend to dominate the strawman payload:  1) a highly sensitive solar-occultation instrument driven by the need to map spatial variations in known trace gases and to detect the suspected, but not yet proven, presence of trace gases whose source could be geochemical or biochemical in nature; 2) a sub-millimeter spectrometer driven by the need to map key trace gases, even in the presence of dust, and to measure winds; and 3) a very high resolution (sub-meter) camera desired for landing site certification. The SDT notes two points: 1) a high resolution (one-meter class) camera could address the MSO surface change science objectives; and 2) the observations of trace gas concentrations and winds are a critical pairing for understanding transport itself and the trace gas distribution, including potential regional sources of bio/geochemically important gases.  The SDT thus suggests that NASA either support the use of MSO for future landing site certification by providing the funding for the more capable camera or remove the requirement, with the attendant reliance on imaging for site certification necessarily provided by current orbiters like MRO. The SDT emphasizes that accommodation of a more capable imager is a cost, and not a mass, issue for a 2013 MSO.

## 7.2  Flight System Complexity

The viewing requirements needed to accomplish the MSO objectives likely involve widespread solar occultation observations, nearly continuous limb viewing measurements, and surface imaging. These lead naturally to a spacecraft that would need to return a large volume of data, that would need to accommodate competing fields of view (possibly including radiators) of its various instruments, and whose orbit would not be fixed in local time. Such requirements could lead to a very complicated operations scenario and possibly a situation in which the spacecraft is overconstrained, resulting in a loss of key science data or in other undesirable trade-offs in data

acquisition. The SDT recommends that the implementation for MSO avoid these pitfalls and that the MSO Project continue to investigate the more promising concepts in this regard. NASA may wish to consider trade-offs between instrument and spacecraft capabilities (e.g., providing mass and dollars to include a small pointing mirror in an instrument). The group did not have time to investigate how this might be described in an AO or, for that matter, to investigate in-depth alternate spacecraft/mission configurations. However, selection of an instrument payload in advance of choosing a spacecraft implementation would help avoid major problems later.

# APPENDIX 1.  MSO Science Definition Team (SDT)

| SDT Members | Affiliations |
|---|---|
| Michael Smith (Chair) | NASA Goddard Space Flight Center |
| Don Banfield | Cornell University |
| Jeffrey Barnes | Oregon State University |
| Philip Christensen | Arizona State University |
| R. Todd Clancy | Space Science Institute |
| Philip James | University of Toledo (retired) |
| James Kasting | Pennsylvania State University |
| Paul Wennberg | California Institute of Technology |
| Daniel Winterhalter | JPL |
| Michael Wolff | Space Science Institute |
| **Ex Officio Members** | **Affiliations** |
| Michael Meyer | Mars Program Lead Scientist, NASA Headquarters |
| John Mustard | MEPAG Chair, Brown University |
| Richard Zurek | JPL |
| Janis Chodas | MSO Project Manager, JPL |
| Tomas Komarek | MSO Mission Concept Manager, JPL |

# APPENDIX 2. TRACING MSO REQUIREMENTS TO MEPAG INVESTIGATIONS

Listed below are the main science objectives proposed for MSO as determined by the SDT. Beside each science objective is listed the MEPAG investigations that would be addressed by that objective. The numbering of MEPAG investigations is taken from the February 2006 report from MEPAG [*Mars Science Goals, Objectives, Investigations, and Priorities: 2006*].

## Atmospheric Composition
*Photochemistry:* IA3, IA4, IB2, IB3, IB4, IIA3, IIB1
*Methane and Other Subsurface Source Gases:* IB1, IB3, IB4, IC2, IC4, IIB1
*Isotopic Ratios:* IB2, IB3, IC2, IIB1, IIB4
*Trace Gas Inventory:* IA3, IB1, IB3, IC2, IIB1

## Atmospheric State
*Dynamics, Transport, and Wind:* IA1, IA4, IIA1, IIA3, IIB2, IIC2
*Climate Characterization:* IA1, IA4, IIA1, IIA3, IIB2, IIC2, IIIA1
*Mesoscale Atmospheric Processes:* IA1, IIA1, IIA2, IIC2

## Surface Change Science
*Regional and Local Changes:* IA1, IIB5, IIIA2, IIIA5
*Polar Science:* IA1, IA2, IIB5, IIIA1, IIIA5

The table below gives the reverse mapping. Under each MEPAG investigation listed are the MSO observations that would provide direct, new information. Note that only those MEPAG investigations that would be directly address by MSO science observations are listed.

## Goal I: Determine if life ever arose on Mars
*Investigation IA1 (Current distribution of water in all its forms on Mars)*
    Water vapor abundance as a function of height, location, season, local time
    Water ice cloud optical depth as a function of height, location, season, local time
    Wind velocity as a function of height, location, season, and local time
    Daily global imaging
    Imaging of gullies and other possible sites of water release
    Imaging of swiss cheese terrain and other polar morphologies
*Investigation IA2 (Geologic history of water on Mars)*
    Imaging of swiss cheese terrain and other polar morphologies
*Investigation IA3 (Phases containing C, H, O, N, P, and S)*
    Trace gas inventory
    Photochemistry species mapping
*Investigation IA4 (Potential energy sources available to sustain biology)*
    Climate characterization
    Photochemistry species mapping

*Investigation IB1 (Distribution of organic carbon)*
    Trace gas inventory
*Investigation IB2 (Distribution of inorganic carbon)*
    Photochemistry species mapping
    Isotope characterization
*Investigation IB3 (Links between C and H, O, N, P, and S)*
    Photochemistry species mapping
    Trace gas inventory and mapping
    Isotope characterization
*Investigation IB4 (Preservation of reduced compounds on near-surface through time)*
    Photochemistry species mapping
*Investigation IC2 (Spatial distribution of chemical and/or isotopic signatures)*
    Trace gas inventory and mapping
    Isotope characterization
*Investigation IC4 (Temporal chemical variations requiring life)*
    Trace gas inventory

## Goal II: Understanding the processes and history of climate on Mars

*Investigation IIA1 (Processes controlling the present distribution of water, $CO_2$, dust)*
    Climate characterization
    Wind velocity as a function of height, location, season, and local time
    Water vapor abundance as a function of height, location, season, local time
    Daily global imaging
*Investigation IIA2 (Search for microclimates)*
    Daily global imaging
*Investigation IIA3 (Production/loss, reaction rates, distribution of photochemical species)*
    Photochemistry species mapping
    Climate characterization
    Wind velocity as a function of height, location, season, and local time
*Investigation IIB1 (Isotopic, noble gas, trace gas composition of present atmosphere)*
    Photochemistry species mapping
    Trace gas inventory
    Isotope characterization
*Investigation IIB2 (Escape rates of key species)*
    Climate characterization
    Wind velocity as a function of height, location, season, and local time
*Investigation IIB4 (Physical and chemical records of past climates)*
    Isotope characterization
*Investigation IIB5 (Stratigraphic record of climate change)*
    Imaging of swiss cheese terrain and other polar morphologies
*Investigation IIC2 (Monitor lower atmosphere, 0-80 km, on synoptic scales)*
    Climate characterization
    Wind velocity as a function of height, location, season, and local time
    Daily global imaging

## Goal III: Determine the evolution of the surface and interior of Mars

*Investigation IIIA1 (Present state, distribution, and cycling of water, volatiles)*
    Climate characterization
    Imaging of swiss cheese terrain and other polar morphologies
*Investigation IIIA2 (Fluvial, subaqueous, other sedimentary processes)*
    Daily global imaging
    Imaging of dunes, ripples, drifts
*Investigation IIIA5 (Surface-atmosphere interactions on Mars)*
    Monitoring changes in albedo patterns
    Imaging of dunes, ripples, drifts

# APPENDIX 3.  LIST OF ACRONYMS

| | |
|---|---|
| AO | NASA Announcement of Opportunity for MSO science selection |
| CTX | Context Camera, an instrument on MRO |
| EDL | Entry, Descent, and Landing portion of a landed mission to Mars |
| ESA | European Space Agency |
| EXOMARS | European Space Agency rover mission to Mars for 2013 |
| FBO | Fed Biz Opps |
| FTIR | Fourier Transform Infrared |
| GCM | General Circulation Model |
| HiRISE | High-Resolution Imaging Science Experiment, an instrument on MRO |
| JPL | Jet Propulsion Laboratory, California Institute of Technology |
| MARCI | Mars Color Imager, an instrument on MRO |
| MEP | Mars Exploration Program |
| MEPAG | Mars Exploration Program Analysis Group |
| MGS | Mars Global Surveyor, in orbit around Mars 1997–2006 |
| MOC | Mars Orbiter Camera, an instrument on MGS |
| MOI | Mars Orbit Insertion |
| MRO | Mars Reconnaissance Orbiter, currently in orbit around Mars |
| MSO | Mars Science Orbiter, to be launched in the 2013 Mars launch opportunity |
| MY | Mars Year, where Mars Year 1 began on 1 April 1955 |
| NASA | National Aeronautics and Space Administration |
| ODY | Mars Odyssey, currently in orbit around Mars |
| SAG | Science Analysis Group |
| SAG-2 | MSO Second Science Analysis Group (report issued May 2007) |
| SNC | A class of meteorites (named for shergottite, nakhlite, and chassigny) thought to have originated from Mars |
| SDT | Science Definition Team |
| TES | Thermal Emission Spectrometer, an instrument on MGS |