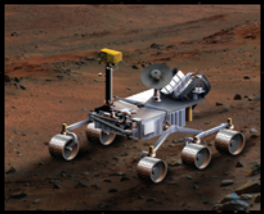
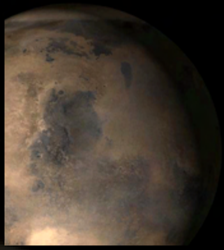
National Aeronautics and Space Administration

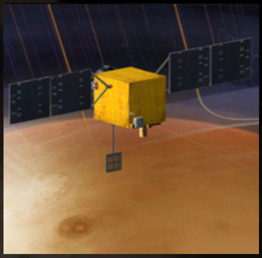
Mars Advanced Planning Group 2006

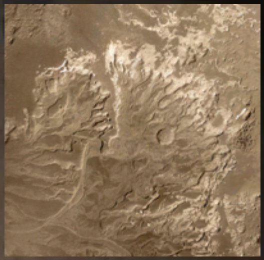
Robotic Mars Exploration Strategy

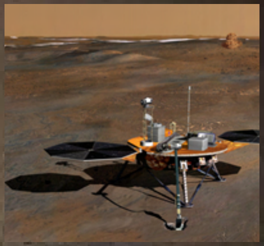
2007–2016







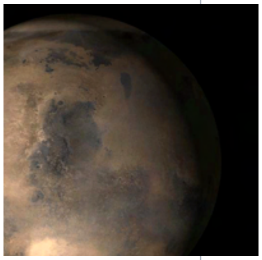


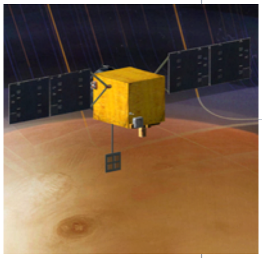


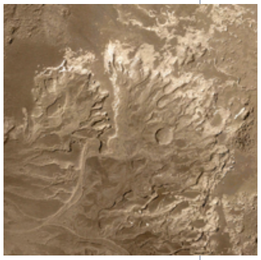
Daniel J. McCleese

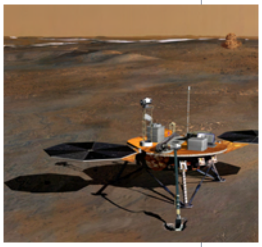
Chair and Editor

March 2006









Contents

1. Introduction

In the summer of 2005, the Mars Advanced Planning Group (MAPG) was charged by NASA with updating the 2002 Mars science exploration plan (*Mars Exploration Strategy*, McCleese et al., 2004) in light of recent scientific findings about Mars, and in response to new constraints on NASA's Mars exploration program. In accomplishing this request, MAPG found it necessary to broaden the scope of the research performed in the exploration program, revise the investigations in the latter half of the coming decade, and adjust the program's architecture by scheduling key missions beyond the horizon of the plan. The objectives of the 2004 plan were retained in creating the revised plan.

MAPG began its work by identifying recent discoveries and findings from data returned from past and still-active missions: Mars Global Surveyor (MGS); Mars Odyssey (ODY); Mars Exploration Rovers (MER); and Mars Express (MEx). The group also explored how the stated intent and potential findings from new mission Mars Reconnaissance Orbiter (MRO) might influence the architecture presented in the 2004 plan. A similar evaluation was performed on the coming-decade missions, Phoenix and Mars Science Laboratory (MSL), which are now well defined but not yet launched. Next, and in light of the above, MAPG identified new and revised investigations, prioritized them, and described the spacecraft platforms that will be needed. Through an iterative process — involving science, technology, engineering and program resources, and priorities — the group created a sequence of investigations and missions that is the program architecture of missions presented here. Supporting the architecture, and presented at the end of the report, are plans for technology development, planetary protection, and telecommunications infrastructure.

The Mars Exploration Program Analysis Group (MEPAG) reviewed a preliminary version of the MAPG plan. MEPAG's review is summarized in this document. It should be noted that the preliminary version evaluated by MEPAG pre-dated the release of the President's 2007 budget, and subsequently MAPG made significant changes to its plan, especially in the out years. Most significantly, beyond 2016, the revised plan describes critical investigations and the missions needed to accomplish them, but specific launch dates and investigation sequence are not provided. It is hoped that unforeseen research opportunities, such as greater international cooperation in the exploration of Mars, will advance at least some of these investigations to earlier years.

The membership of the Mars Advanced Planning Group is shown in Table 1.

Table 1. Mars Advanced Planning Group Members.

SCIENCE	ENGINEERING
Dan McCleese *(Chair)* *Jet Propulsion Laboratory, California Institute of Technology*	
Mike Meyer *NASA Headquarters*	Mark Adler *Jet Propulsion Laboratory, California Institute of Technology*
Ray Arvidson *Washington University in St. Louis*	Bobby Braun *Georgia Institute of Technology*
Bruce Banerdt *Jet Propulsion Laboratory, California Institute of Technology*	Jim Campbell *Jet Propulsion Laboratory, California Institute of Technology*
Dave Beaty *Jet Propulsion Laboratory, California Institute of Technology*	Chad Edwards *Jet Propulsion Laboratory, California Institute of Technology*
Joy Crisp *Jet Propulsion Laboratory, California Institute of Technology*	Samad Hayati *Jet Propulsion Laboratory, California Institute of Technology*
Dave Des Marais *NASA Ames Research Center*	Frank Jordan *Jet Propulsion Laboratory, California Institute of Technology*
Bruce Jakosky *University of Colorado at Boulder*	Rob Manning *Jet Propulsion Laboratory, California Institute of Technology*
Scott McLennan *State University of New York at Stony Brook*	Richard Mattingly *Jet Propulsion Laboratory, California Institute of Technology*
Mark Richardson *California Institute of Technology*	Sylvia Miller *Jet Propulsion Laboratory, California Institute of Technology*
Glenn MacPherson *National Museum of Natural History, Smithsonian Institution*	Greg Wilson *Jet Propulsion Laboratory, California Institute of Technology*
Marguerite Syvertson *Jet Propulsion Laboratory, California Institute of Technology*	

2. Context for 2006 Plan

The 2004 plan for the exploration of Mars was predicated on a number of scientific, technological, and programmatic assumptions. Some of the events behind these assumptions have come to pass while others did not or are no longer valid. One of the guiding principles of the 2004 plan was the scientific and programmatic need for multiple lines of investigation pending new knowledge, e.g., a past or present habitable environment on the planet. Discoveries made by near-term missions could, it was thought, raise the priority of one course of investigation above others. Four so-called Pathways of exploration were identified (see *Mars Exploration Strategy*, 2004). A framework for making decisions was described — for example, selecting one of the four Pathways in order to respond to a new research goal and determining how a change in budgetary resources or a scientific discovery should shift the program from one Pathway to another. Thus, the 2004 plan indicated that both understanding and programmatics play important roles in the overall direction of the scientific program.

The new 2006 plan, presented here, responds both to new understanding and to changes in programmatic direction. Specifically, results from the missions launched between 1996 and 2003 show that Mars was once wet — something only surmised previously — and that large quantities of water ice remain on and near the surface. We now believe that surface environments were probably habitable billions of years in the past, and that the diversity of environments on Mars through time was far greater than had been appreciated. Together, these findings suggest that the search for evidence of life on Mars has scientific merit and that significant progress is being made in determining where and when life may have evolved on the planet. In the programmatic realm, the nation’s Vision for Space Exploration, the associated new priorities for NASA, and the costs for Space Shuttle Return to Flight have meant that the 2004 plan for robotic exploration of Mars is overly aggressive.

The 2006 plan for Exploring Mars (2007–2016) reflects greater clarity in understanding the history of Mars and acknowledges the reduction in resources available for future exploration. MAPG has selected the Pathway in the 2004 plan that seeks to understand the processes through time that underlie the enormous diversity of Martian environments, identifies the habitable sites with time, and narrows the search for evidence of life.

2.1 Programmatic Context for Exploration in the Coming Decade

Despite recent spectacular successes, the Mars Exploration Program has suffered successive reductions in annual budgets. Additionally, out-year growth is set at only 1.5%, less than the inflation rate. As a consequence of declining support for the Mars Program, all planned human precursor missions have been eliminated, the Mars Telecommunications Orbiter has been canceled, and the feed-forward technology program has been reduced by about 50%. Although the near-term priorities of MRO, MSL, and Phoenix have been maintained, the program is fragile, and earlier planned missions for the next decade are either fiscally unfeasible, highly constrained, or fewer in number. Future flagship missions will become progressively more challenging as inflation erodes the buying power of the Mars budget.

NASA understands that the perceived public appeal of the Mars Exploration Program rests with the overarching goal of learning whether life ever arose on Mars. Under the current fiscal constraints, the program must maintain public support while meeting scientific goals. NASA also appreciates that otherwise scientifically worthy missions must be deferred. The high-priority mission, Mars Sample Return, is problematic both for fiscal and programmatic reasons. This mission is costly, probably using the resources of two to three mission opportunities. The technology development requires a long lead time. Furthermore, we are not confident, from what is now known about Mars, that MSR would soon be able to directly address the question of life. Confidence that the life goals can be addressed by returning samples to Earth laboratories may come from Phoenix or MSL, if either detects the elusive organics last searched for by Viking.

Agency priorities for space exploration have been disseminated widely. The group has endeavored to create a plan for the future exploration of Mars that reflects these priorities. Working as an integrated team, scientists, technologists, engineers, and program representatives have arrived at a strategy that is significantly less ambitious than prior plans (see *Mars Exploration Strategy*, 2004), but one that is robust and exciting. We know that Mars is capable of revealing secrets of such importance that priorities change.

3. Status of Mars Exploration

The overarching goals of NASA's program of Mars exploration are presented in Figure 1. Life, climate, geology, and preparation for human exploration have a common, measurable link — water. For Mars (like Earth), water is central to the planet's history; it is also the primary reason for our interest in it as a potentially habitable world. Detailed discussion of the goals, objectives, and investigations may be found in *Greeley* (2001) and *MEPAG* (2006).

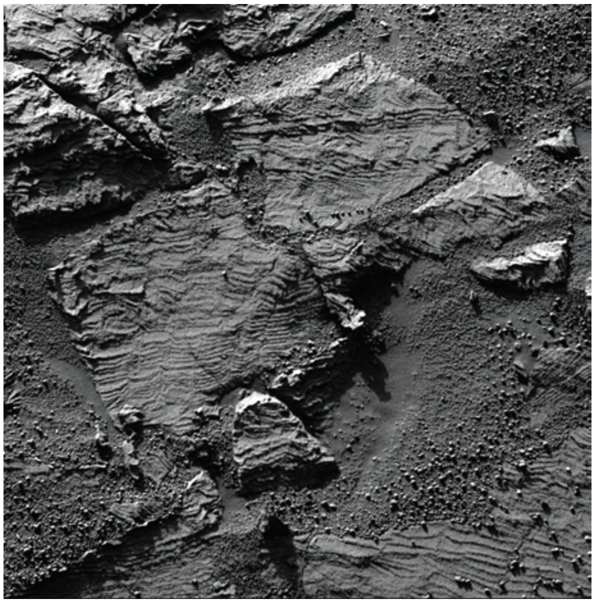
Figure 1. Goals of the Mars Exploration Program.

3.1 Life Goal: Accomplishments to Date and Next Steps

NASA's program of Mars exploration has as its highest priority establishing that life is or was present on Mars, *or,* if life never was present, understanding why not. A multidisciplinary scientific exploration is required in order to determine the evolution of the Mars system and to determine whether it is or could ever have been habitable. In these studies it is essential that both the current distribution and the geological history of water be documented. The chemical and other sources of biologically usable energy should be assessed, and the chemical compositions, physical states, and crustal reservoirs of the elements C, N, S, O, H, and P determined. In particular, understanding the geochemical cycles of carbon — namely, how carbon has been processed and distributed on Mars during its history — is critical for understanding where to look for life on Mars (in both space and time) and how life, if ever present, might have originated and evolved. By studying the Martian carbon cycles — for example, the chemical nature of organic carbon deposits — the existence of life (extant or extinct) might be revealed, and such results are likely to influence strongly strategies to search for other kinds of biosignatures, namely structures, chemicals, or patterns that required a biological origin. The search for life can entail both observing actual biological processes, as the Viking landers attempted, and searching for biosignatures. Present life might produce observable temporal changes in chemistry during the period when a lander experiment is conducted. However, possible nonbiological reactions might create ambiguities and must be understood. Examples of biosignatures include complex organic compounds, certain minerals, diagnostic shapes, and/or chemical compositions of structures. It is fortunate for our purposes that because certain biosignatures can be preserved long after they were created, they can indicate life's former presence in the geologically distant past. In all aspects of this research, it will be crucial that potential sources of forward contamination, organics or microbes, on landed spacecraft be identified and/or excluded.

Improved Knowledge to Date

Investigations conducted thus far have not detected the existence of past or present life on Mars. However, the possibility that life may have evolved there has been strengthened by recent investigations. Observations from the Opportunity and Spirit rovers and from orbit have confirmed that liquid water has chemically weathered the crust. The Opportunity rover discovered in Meridiani Planum aqueous sediments rich in sulfur, chlorine, and iron oxides. The Spirit rover found extensively aqueously altered volcanic rocks in Gusev Crater. Orbiters have found deltaic deposits and layered sediments that might have been deposited by water. And orbiters have also discovered crystalline iron oxides, extensive sulfate deposits, and perhaps clay minerals. These deposits indicate that the chemical consequences of aqueous processes have been extensively preserved. Liquid water was not only available; it also participated in rock weathering reactions, such as iron oxidation, that created potential sources of energy for life. The size and extent of aqueous deposits such as sulfates indicate that these processes persisted for long intervals of time. It should be mentioned that although the Mars meteorite ALH84001 spurred a vigorous debate about the putative evidence of ancient life on Mars, the divergent conclusions are not resolved, in large part due to a lack of geologic context of the specific Martian environment from which the meteorite originated.



The Mars Exploration Rover named Opportunity found fine-scale layering patterns, called "cross laminations" and "festoons," at the edge of "Erebus Crater" in Meridiani Planum. The detailed geometric patterns of these nested sets of concave-upward layers imply the presence of small sand ripples that form only in water on Earth.

Every mission flown thus far has reinforced the view that the Martian crust is complex and diverse. Liquid water was widespread on the surface of Mars early in the planet's history, at least until the middle Noachian (the period from the birth of Mars to 3.5 to 3.8 billion years ago). Several data types point to early atmospheric conditions on Mars that sustained a hydrological cycle that included surface precipitation, run-off, and accumulation as streams and lakes. Later in Martian history, potentially habitable environments were present locally as groundwater emerging onto the surface, fluvial channels, and lakes sustained by interactions between magma and ice-rich soil, as well as impacts. Also consistent with the data that we have in hand are large episodic volcanic eruptions and climate cycles driven by Martian orbital obliquity variations that might have driven a global hydrological cycle. Understanding gleaned from data collected thus far does not rule out melting of the shallow cryosphere, increasing atmospheric density into the range of surface pressures able to sustain liquid water on the surface.

One of the most intriguing and hotly disputed findings related to the Life goal is the published interpretations of the putative detection of methane in the Martian atmosphere. From both ground-based and MEx observations, methane has been inferred to exist at levels that are consistent only with there being a highly active source of the gas on Mars. Methane is predicted to have a very short life in the Martian atmosphere (only several hundred days), suggesting that the gas is emerging from the surface/subsurface. Two processes for creating methane have been published: a byproduct of living organisms, and active geology such as volcanism or the chemistry of water interacting with rocks at elevated temperatures. Any of these alternative sources are tremendously important for the search for life, even if only as evidence of a warm, possibly wet, habitable environment.

Potential Outcomes of Near-Term Investigations

From orbit, the deep-sounding radar instrument on MEx (ESA) will continue and the shallow-sounding MRO radar will search the subsurface for reservoirs of water ice and aquifers. These reservoirs may provide transient sources of surface water, habitats for present life, or clues to hydrological cycles in the recent past. MRO will also globally map deposits of aqueous minerals and sediments indicative, perhaps, of more ancient habitable environments. Both MEx and MRO have enormous potential to discover potential landing sites much more promising for the Life goal than those currently known. These probably include fluvial and lacustrine sediments, thermal spring deposits, and other chemically altered deposits that preserved records of ancient potentially habitable and inhabited environments.

Best Next Steps for the Life Goal

The Phoenix Scout lander is well advanced in its development for a 2007 launch to the northern latitudes of Mars. The first probe of a modern water/ice environment, Phoenix will analyze near-surface ice deposits, detected from orbit by ODY, to search for organic or biological molecules. Phoenix will also characterize the present hydrological cycle involving the exchange of water between the cryosphere and atmosphere. The second mission in the coming decade, MSL (2009 launch), will explore in detail the light-element chemistry of Martian rocks and soils. The analytical laboratory onboard the MSL rover will also enable, for the first time, definitive mineralogical, geochemical (including isotopic), and organic surveys of rocks and soils at high priority sites. In addition, MSL will investigate surface environments searching for sources of energy, including energy from chemical reactions, essential to life.

MSL addresses the putative discovery of methane in the Martian atmosphere, as well, by making highly sensitive and precise measurements in an attempt to detect the gas and determine its abundance over time. It is unlikely that MSL will identify the sources of the gas, given that its measurements will be limited to a localized region of the surface. However, progress in the Life goal might be cast well ahead of our current expectations if the source(s) of methane are, in the future, identified with sufficient resolution and characterized globally from an orbiting platform. We can easily imagine that landed missions might be directed to those sources to investigate further.

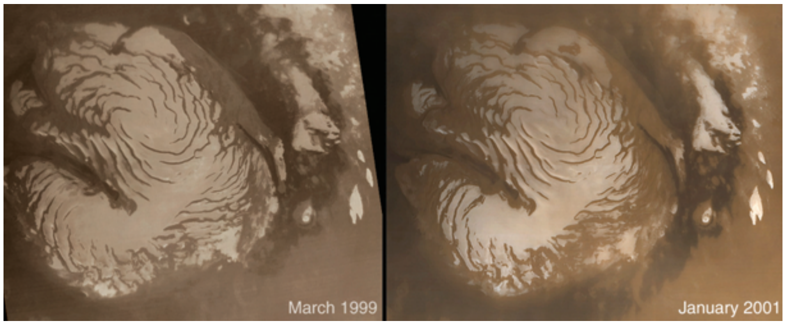
Beyond MSL, future landing sites will be selected with an eye to accessing deposits having high potential for accumulating and preserving organic and other types of biosignatures. The search for organics in sedimentary deposits will continue to be among the highest priority investigations for the program, until such time that they are found. If MSL lands at a site with the potential to preserve organics and does detect such material, subsequent missions must characterize the material, identify its provenance, and search for biosignatures. It seems reasonable that an astrobiological investigation package be sent to the same site. Sample return will play a crucial role in these investigations by enabling definitive life-detection tests performed on rocks and soils in laboratories on Earth. Should MSL fail to find organics or biosignatures of any kind at its landing site, we think it prudent to extend the search to additional sites.

3.2 Climate Goal: Accomplishments to Date and Next Steps

Climate change is a central theme of Mars' story. Hints of a watery past have for decades motivated our study of the planet. Variations in climate may have yielded environments that were habitable; certainly they have made Mars a very diverse and potentially Earth-like planet. From studies of Earth, and initial studies of Mars, we know that climate has two interdependent elements: history and process. While "history" has received a great deal of attention in the Mars program and much progress has been made to date, the "process" has had a lower priority. Progress in understanding climate processes correspondingly lags behind. In NASA's exploration program, the history of Martian climate has traditionally been treated as a component of the Geology goal, while the Climate goal places greater emphasis on the understanding of processes.

Improved Knowledge to Date

Progress in understanding climate processes in the last decade has come primarily from the observations from the Thermal Emission Spectrometer (TES), Mars Orbiter Camera (MOC), and radio science from the MGS orbiter. Together, these instruments have operated for more than four Martian years — a sufficient period to characterize the mean state of the lower atmosphere — the seasonal cycle and the nature of the short-term climate perturba-



Two images of the Mars North Polar Cap during summer were acquired almost exactly one year apart by the Mars Orbiter Camera (MOC) on Mars Global Surveyor (MGS). Differences in frost cover (decreased or increased) between the two images represent the amount of evaporation or deposition expected over a five-month period. What could account for such changes in the heat budget for the polar caps from one year to the next is not known.

tions. These climate regimes of the lower atmosphere are key to understanding how the climate might have changed as the orbital elements and/or atmospheric mass and composition changed over much longer timescales — hundreds of thousands to tens of millions of years. From Earth-based and spacecraft observations we know that dust storms of various sizes drive large interannual perturbations, the variety and evolution of which is much better recorded (if not understood) with the MGS data. The degree to which the seasonal cycles of temperature, dust, and water vary from year to year have also been discerned, and bounds put on the perturbing potential of dust in the present climate. MGS and ODY observations of the residual polar caps have also shown interannual variability (and a close coupling between water and CO_2 ice) that may be central to understanding the fastest parts of the volatile cycles.

In conjunction with ODY and MEx observations, the range of meteorological phenomena operating within the atmosphere has been cataloged. Observations of the crucial boundary layer are much less complete. The boundary layer controls surface–atmosphere interactions, including water vapor exchange with the surface/subsurface that ultimately controls whether water is stable. Mars Pathfinder, MER, and radio science observations have provided useful snapshots of behavior, but in sufficient isolation that they cannot uniquely constrain process (the relationship between forcing and response of surface–atmosphere mixing). The boundary layer is particularly important to exploration because it is in this region of the atmosphere that all surface missions must operate, including during descent and landing.

The upper atmosphere has only been sparsely sampled by accelerometer data from spacecraft aerobraking into circular orbits. These data suggest that large perturbations in density as a function of latitude and longitude result from propagation of waves from the lower atmosphere. Here, too, safe operation of spacecraft depends on knowledge of the atmosphere and its variability. Vertical mixing and atmospheric loss rates for trace species have not been examined despite the proposed role of atmospheric loss in climate evolution. Within the field of climate history, the detection of subsurface water by ODY and the suggestion of recent glacial deposits imply that recent climate change may have been very dramatic.

Potential Outcomes of Near-Term Investigations

In the coming decade, a great promise for progress comes from MRO observations. This data set should reveal the lower atmosphere in greater detail, especially as regards vertical resolution, water vapor distributions, and aerosol (dust and ice) microphysics. If MRO continues to operate for a number of Martian years, it will not only extend the crucial time series started by MGS (since the characteristic timescale for variability in dust storm behavior is very much greater than one year, the value of an extended time series is very much greater), but allow the relationship between dust, water, and the circulation to be understood in quantitative detail. Unfortunately, the landed spacecraft in the coming decade may not carry investigations of sufficient capability to quantitatively constrain boundary layer processes. While useful qualitative snapshots of the boundary layer aerosol distribution should be provided by Phoenix, a quantitative understanding of surface–atmosphere fluxes will remain beyond examination. The high latitudes are of unique importance within the climate system because it is there that the thermal balance of water and CO_2 deposits determines the thickness and humidity of the atmosphere, and it is there that the most likely "readable" record of climatic variation exists (in the polar layered deposits).

Best Next Steps for the Climate Goal

Attempts to place the chemical and morphological evidence of liquid water on the ancient surface in a workable context with plausible climate models have thus far failed. Vital to the mystery of the ancient climate is the evolution of the Martian atmosphere, which is little understood. Future investigations are badly needed to quantify the escape of the present atmosphere so that extrapolations can be made to determine the amount and composition of the ancient atmosphere. Investigations onboard the failed Nozomi spacecraft would have addressed some of these needs. The early NASA Mars Aeronomy mission would, if it had not been abandoned after the loss of Mars Observer, have contributed a great deal.

The weather and modern climate of Mars have been observed from space, but the near-surface meteorology has been only barely touched. The atmospheric boundary layer of Mars controls the initial lifting of dust from the surface, as well as weathering and volatile exchange at the surface, and it is where robotic and human explorers operate. As soon as is affordable, capable meteorology instruments should be distributed widely over the surface in a network of long-lived stations. Studies of such a network indicate that 4 to 18 stations are needed, depending on the precise nature of the objective, and each having a life of 4 to 10 years.

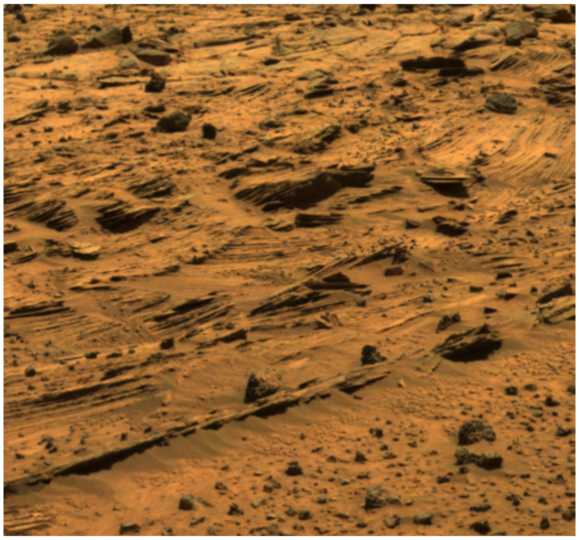
Although Phoenix will reach the high northern latitudes, no investigations yet planned will access the record of past climates captured in the polar layered terrains. Orbital measurements suggest that these landforms may be the best-preserved records of climate over the last 100 million years in the solar system. In addition, given that the environment at the northern latitudes is potentially habitable by human explorers — a unique combination of abundant water ice and abundant summertime solar insulation exists there — it will be prudent to investigate this region in future.

3.3 Geology Goal: Accomplishments to Date and Next Steps

Improved Knowledge to Date

From the initial flybys of Mariners 4, 6, and 7 to the current MER rovers traversing the surface as three active orbiters circle overhead, the exploration of Mars has revolutionized our understanding of the geological evolution of the planet and the role that water has played throughout Martian geological history. This understanding has been complemented and extended by some three dozen meteorites with isotopic signatures indicative of a Martian origin. Only recently, with the wealth and variety of data types, have we truly appreciated the remarkable geological diversity of Mars and the complex tectonic, volcanic, and stratigraphic evolution exhibited, particularly early in geologic time.

Investigations conducted thus far from orbit indicate that an internal dynamo generated a magnetic field very early in Mars history — providing, for any organisms that may have been present, a protective shield that has long since disappeared. Massive volcanic emissions of water vapor, carbon dioxide, and other gases may have caused greenhouse warming of the surface. Fluvial channel systems formed during this early period and open or ice-covered lakes and shallow seas may have existed at least on an ephemeral basis. As the rate of volcanism and supply of greenhouse gasses declined over time, we hypothesize that conditions grew much colder and surface liquid water less viable. Although volcanism diminished over time, crater counts and analyses of Martian meteorites indicate that igneous activity persisted intermittently, perhaps presenting transient greenhouse warming or active hydrothermal systems that created conditions suitable for liquid water to exist.



At "Home Plate" in the "Columbia Hills" of Gusev Crater, the Mars Exploration Rover named Spirit examined complex layered rock that indicates alternating erosional and depositional periods. Scientists suspect that rocks here may have been formed in the aftermath of a volcanic explosion or impact event.

MER and MEx provide the most recent illustration of the important role of liquid water in the past. On its traverse into the Columbia Hills, the rover Spirit uncovered rocks that were altered by salty groundwater. On the Meridiani plains, Opportunity found evidence for cross-bedded, evaporitic sulfate-rich sandstones that formed in dune — interdune — playa lake depositional settings, with subsequent modification by corrosive groundwater. MEx data reveal abundant hydrated sulfate minerals in association with layered deposits such as those in Meridiani Planum and Valles Marineris. This result suggests that Mars, when wet, was dominated by acid-sulfate aqueous systems that would have precluded formation of the so-called missing carbonate deposits. Clay minerals occur, but only in older cratered terrains, again consistent with a warm, wet early Mars. The weight of evidence, from spaceborne and meteorite data, shows that Mars had and probably still has an active hydrological cycle with environments near the surface that are harsh but nevertheless habitable by terrestrial standards.

Dynamical calculations indicate that Mars undergoes changes in orbital obliquity, eccentricity, and positions of the equinoxes over timescales of ~10^4 to 10^7 years (akin to Earth's Milankovitch Cycles). These cycles have modulated characteristics of the climate and the geological response, including groundwater fluctuations, atmospheric pressure, and the ability of the atmosphere to transport water vapor and ice, carbon dioxide, and dust.

Potential Outcomes of Near-Term Investigations

MRO will provide high-resolution spectral maps and images that will allow the identification of sites with mineralogical evidence of habitability at an unprecedented fine scale. Ground-penetrating radar will map compositional discontinuation and layering that may be indicative of groundwater and subsurface ice. Phoenix responds to the ODY findings of the presence of shallow water ice at high northern latitudes. Phoenix will characterize the chemistry, mineralogy, and isotopic composition of evolved gases in surface and subsurface soils and ices. Its imaging system will be used to map the periglacial geological setting of the landing site. MSL will provide an unprecedented geological, chemical, and mineralogical exploration of a potentially habitable site identified from orbit.

Best Next Steps for the Geology Goal

In order to understand the geological evolution of Mars, on all timescales, and the history of habitability, it is crucial that future investigations characterize thoroughly the geological diversity of the planet and begin to investigate the planetary processes responsible for it. This will be best accomplished through a combination of detailed in situ examination using surface rovers and landers coupled with geophysical investigations and sample return from carefully selected sites. The quality and value of scientific results from surface missions depend upon the landing site selected and the completeness of the available geological, climatological, and geophysical context. The former can be provided by carefully selected orbital mapping to characterize the complexity found at the surface, such as that to be provided by MRO. A network of landers, carrying seismic sensors, heat flow probes, and the capability for making high-precision geodetic measurements is needed to better understand the structure, state, and processes of the Martian interior in order to ascertain thermal and geological evolution of the planet that is responsible for the surface we see today.

Understanding of the interior of Mars is fundamental to the interpretation of the surface record. The delineation of the elementary interior structure (core, mantle, crust) and the establishment of basic thermal boundary conditions for the planet's thermal history are essential components to understanding Mars and its history. Seismic monitoring, heat flow measurements, and dynamical measurements of Mars' rotation are needed and can be best accomplished by a geophysical network.

The putative detection of methane in the Martian atmosphere has important implications for the future direction of geological investigations as well. The short lifetime predicted for methane in atmosphere suggests that there must be a source or sources active today.

In the coming decade, additional rover missions — both exploration rovers based on the MER concept and specialized rovers carrying analytical laboratories like MSL — will be required to continue to identify and characterize Mars geological diversity. Whether exploring for diversity or detailed study of a site is preferred in future will depend on the findings of missions like MRO. In either case, we seek to provide an historical and process context that explains the diversity found on Mars.

Understanding the formation and evolution of Mars will, in large part, come from samples of rock, soil, and atmosphere returned from carefully selected sites. In situ analytic instruments will not overtake the best instruments in laboratories on Earth for a great many critical measurements. The more we understand about Mars from in situ and remote measurements, the more valuable will become samples of Mars in Earth's laboratories available for precise corroborated analyses.

3.4 Preparation for Human Exploration Goal: Accomplishments to Date and Next Steps

Improved Knowledge to Date

The state of knowledge of Mars as it relates to human exploration was last evaluated by MEPAG in 2005. That analysis incorporated results from the missions MER, ODY, MGS, and MEx through early 2005. The MAPG judges that analysis to be up to date. One of the key conclusions of MEPAG is that of the risks in the Martian environment to which humans could be exposed, some 20 of these risks can be mitigated through precursor scientific investigations. Four risks, addressable by precursor investigations, stand out as being of particularly high priority:

- Water accessibility/usability at the landing site is not as assumed.
- Wind shear and turbulence effects on entry, descent, and landing (EDL) and takeoff, ascent, and orbit (TAO) are greater than systems can tolerate.
- The potential for Martian life to affect Earth's biosphere.
- Adverse effects of dust on mission surfaces/systems (electrical, mechanical, chemical, biological).

Another risk addressable by precursor missions is radiation exposure. Advanced flight engineering development, related to technology and infrastructure, is another path for mitigating risks to human explorers.

As recently as last year, the "Safe on Mars" program element of the Mars Exploration Program (Hauk et al., 2002) identified the need for advances in EDL systems; propulsion; Mars surface in situ resource utilization (ISRU); nuclear power systems for the Martian surface; and nuclear thermal rockets. The Agency's fiscal realities have forced a deferral of program activities that would have advanced these areas. Consequently, while scientific robotic missions will continue to inform us on the Martian environment, and its hazards and potential mitigation measures, costly technical development and flight demonstrations are on hold.

Potential Outcomes of Near-Term Investigations

The scientific objectives of Phoenix are well aligned with the ground-truth tests needed to evaluate predictions of accessible water ice at high latitude. Phoenix will be an important first step in addressing the water-related risk mentioned above. Future landed missions will pass through the Martian atmosphere, giving us profiles of Martian atmospheric density and wind structure. However, these profiles will be but snapshots in time and space of highly dynamic phenomena. MRO will create planetary-scale maps of critical atmospheric properties, e.g., density, dust and, through data assimilation, winds. Both long-term atmospheric state and variability and short-term weather must be characterized. Information of relevance to the back planetary protection risk will be developed by Phoenix and MSL. However, none of these missions will be sufficient to retire that risk.

Finally, MSL will continue the lessons we are learning from MER about the effects of dust on landed systems. Specifically, MSL will deliver critically needed mineralogy information about the Martian dust that will permit realistic engineering design and simulations for human health and mechanical survivability issues.

Although NASA has deferred activities leading to technological readiness for human missions, the robotic program will extend present capabilities for landing more massive vehicles and improved landing accuracy. Here, MSL will employ guided aeroentry that will improve landing accuracy from ~100 km to ~10 km. Future landed robotic missions may further improve the landing accuracy to ~100 meters. Also, the application of new parachute technologies will permit landed mass increases from today's ~0.2 metric tons for Mars to more than 1.5 metric tons. Human health issues will be addressed, as well, through direct measurements of high-energy cosmic rays and secondaries by MSL.

Best Next Steps for the Human Exploration Goal

The return of a sample of Mars would advance preparations for human exploration the most of any mission currently under study. A sample return mission will demonstrate, at subscale, several engineering efforts needed for humans, including Mars ascent methodologies and rendezvous in Mars orbit.

MSR would permit the complete characterization of dust collected from at least one landing area. The presence or absence of Martian biology in a sample from a potential human landing site could be confidently assessed. Other landed missions will be needed to mitigate atmospheric risk. For example, to confront atmospheric risks, the most effective approach is a network mission, in which simultaneous measurements of the Martian atmosphere are made at multiple locations distributed over the planet. Data from a meteorology network would constitute particularly valuable input into a Martian atmospheric model for human landings and operations.

A systematic resource exploration program needs to be designed, possibly an orbital geophysical reconnaissance followed by landed ground truth. These landed tests will be dependent upon, as yet undesigned, water-relevant sample acquisition systems and analyses systems.

4. Science Pathway & Implementation Strategy

Mars exploration proceeds in a sequence and timing that is responsive to several factors. Chief among the influences on NASA's Mars exploration are:

- Scientific objectives
- Discovery and accumulated understanding
- Program direction and resources
- Launch opportunities (at 26-month intervals)
- Response time for missions to investigate findings from a prior mission (typically 6 to 7 years)
- Readiness of enabling technology for spacecraft and instruments

The Mars Exploration Program employs an architectural framework to describe the content and sequence of investigations and missions, e.g., geochemistry objectives addressed from a mobile platform, consistent with these and other factors. The planning process is iterative, using a team of scientists from the Mars community, engineers, technologists, and program leaders. In the plan presented below, approximately a dozen architectures were created and evaluated by the team. Some of the architectures evaluated were intentionally dominated by one of the above factors, while others attempted to achieve a best balance among all the known constraints.

4.1 Mission Architectures

Mission architectures were evaluated for scientific value, technical feasibility, and alignment with programmatics. The priority investigations described in the goals section above can be associated with specific measurements, instruments needed to make those measurements, and spacecraft platforms from which observations can be performed. The instruments used by MAPG for planning purposes are examples only. They are intended only to demonstrate that measurements can be made with existing technologies or, alternately, that technologies must be developed. Strawman instruments are also useful for scaling payload mass, size, and other platform-specific requirements that, in turn, size spacecraft and estimate mission cost.

Aggregates of investigations in four distinct potential missions are identified in this plan. They are, in no priority or other ranking:

MARS SCIENCE ORBITER

- *Atmospheric evolution*
- *Atmospheric chemistry and surface processes*
- *Surface science support by emplacing telecommunications infrastructure*

MARS SAMPLE RETURN

- *Habitability*
- *Search for biosignatures and evidence of past and present life*
- *Climate evolution*
- *Geology, geochemistry, mineralogy, and petrology*
- *Origin and evolution of the planet and its atmosphere*
- *Prepare for human exploration*

GEOPHYSICAL AND METEOROLOGY NETWORK

- *Origin and evolution of habitable planets*
- *Structure of the Martian interior*
- *Near-surface meteorology and global circulation*

ROBOTIC SURFACE ROVER

- *Search for and characterize habitable environments*
- *Search for biosignatures if organic material is detected by prior missions*
- *Geology, geochemistry, mineralogy, and petrology*
- *Characterize and contextualize environmental diversity in space and time*

Currently, the Mars Exploration Program includes Mars Scouts, an additional mission type that will remain critical in the coming decade. The first Scout in the Mars Exploration Program is the Phoenix lander (2007 launch). Complementing the science in strategic missions, Mars Scouts are Principal Investigator–led missions constrained by capped cost to modest scope and focused by science teams through competitive evaluation.

4.2 Costing Program Architecture Options

Program goals, resources, and constraints are critical to devising feasible architectures. For this plan and at NASA's Mars Program direction, program resources for 2007 and beyond are roughly $600 M/yr. Section 2.1 describes additional program constraints. These constraints have substantive impact on the viability of architectures. For example, the 2002 plan argued that MSR was first in scientific priority, and the first major mission in the coming decade should return samples. The 2006 plan departs from the earlier plan by delaying MSR into the distant future, primarily as a result of cost constraints.

4.3 Consensus Planning

Scientists represented by MEPAG have not reached a consensus on the relative priority of the strategic missions proposed in this plan. The MEPAG Science Analysis Group that reviewed MAPG's plan enthusiastically endorsed the plan, but provided no assessment of mission priorities. The National Research Council's Space Studies Board (Belton et al., 2002) encouraged NASA to pursue the return of samples from Mars as soon as possible and frequently. Similarly, that report urged NASA to conduct a mission of network landers for the purpose of seismic and meteorology investigations. Reflecting the absence of a clear scientific preference for mission (specifically in the 2016 launch opportunity) or mission sequence, yet encountering strong programmatic drivers, the MAPG plan responded by favoring the architectures that delayed MSR and the network mission. MAPG brought in situ mobile investigations forward in time. We were also persuaded by arguments in favor of a prompt response to the findings of the MSL (2009 launch) mission and by the importance of following up on the recent putative discovery of methane in the Martian atmosphere.

4.4 Exploration Plan 2007–2016: Missions, Architecture, and Attributes

MAPG established the sequence of investigations and missions, scientific content of each mission, and type of spacecraft by trading architecture design against requirements. The architecture that addresses the plan for 2007–2016 is presented in Figures 2a and b, and each mission is described briefly in text illustrations and tables, where additional details are provided. The Group identified an architecture that is optimized within the requirements of science, implementation, and program

— the former are derived from the scientific principles discussed in this report; the latter two components include engineering, technology, and program priorities and resources.

Figure 2a indicates that at two junctures, there are options for the mission flown. The first occurs in 2011, at which time MAPG proposes that either NASA proceeds with a competitive Scout mission or the Mars Science Orbiter (see the MSO science description in brief below and in detail in the MEPAG Science Analysis Group report on MSO, B. Farmer et al. 2006). The mission not launched in 2011 would be flown at the next launch opportunity in 2013. At the time of writing, we understand that NASA intends to make the decision on which mission will launch in 2011 in spring 2006 when MRO is confirmed to be safely in orbit and system checks are complete. Note that a potential outcome of the MSO mission is the discovery of an active source of methane on the Martian surface. A discovery of such importance, whether the methane is biogenic or geologic in origin, would benefit the future program most if it were to come in 2011.

Figure 2a. Mars Program Architecture.

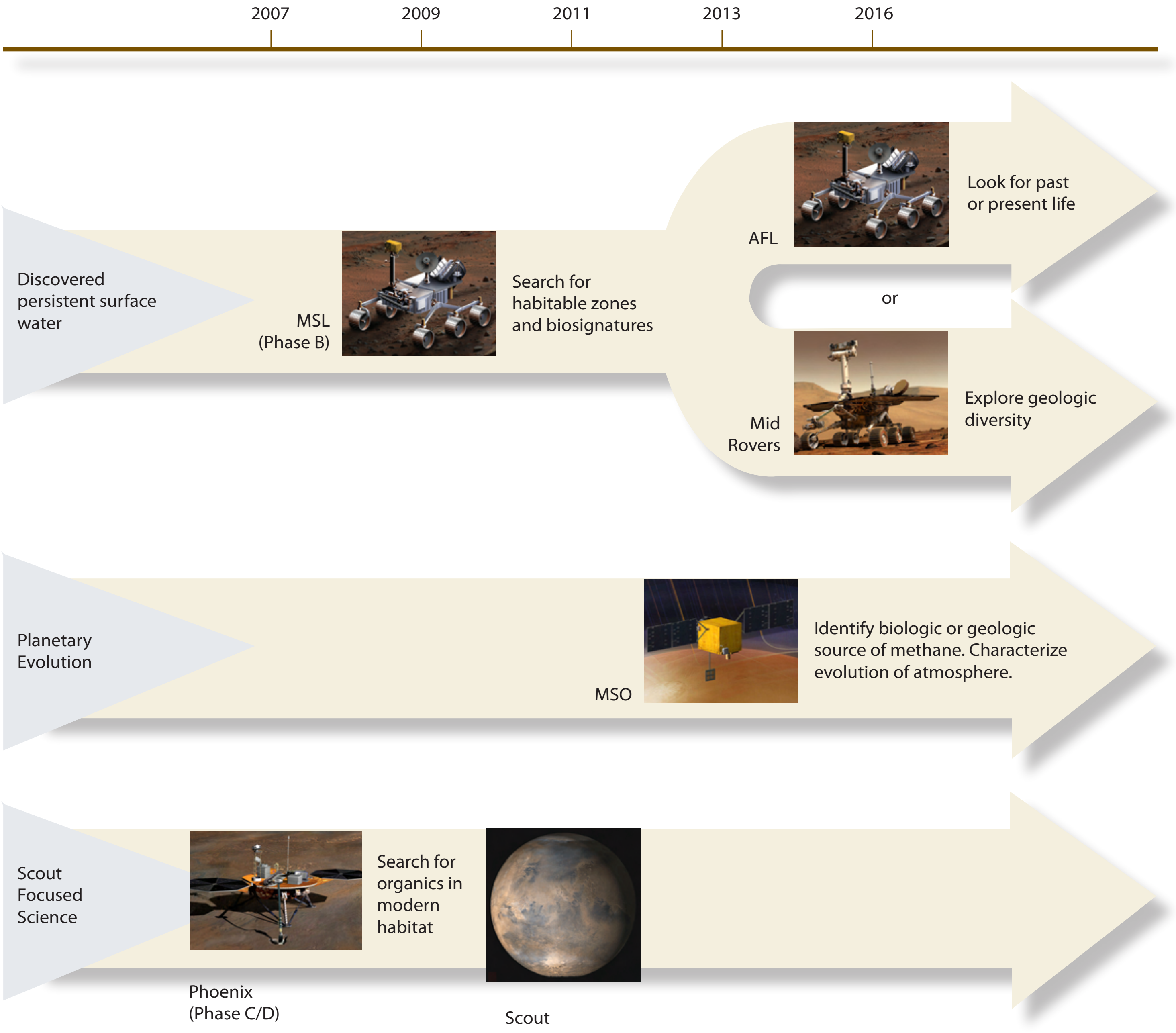
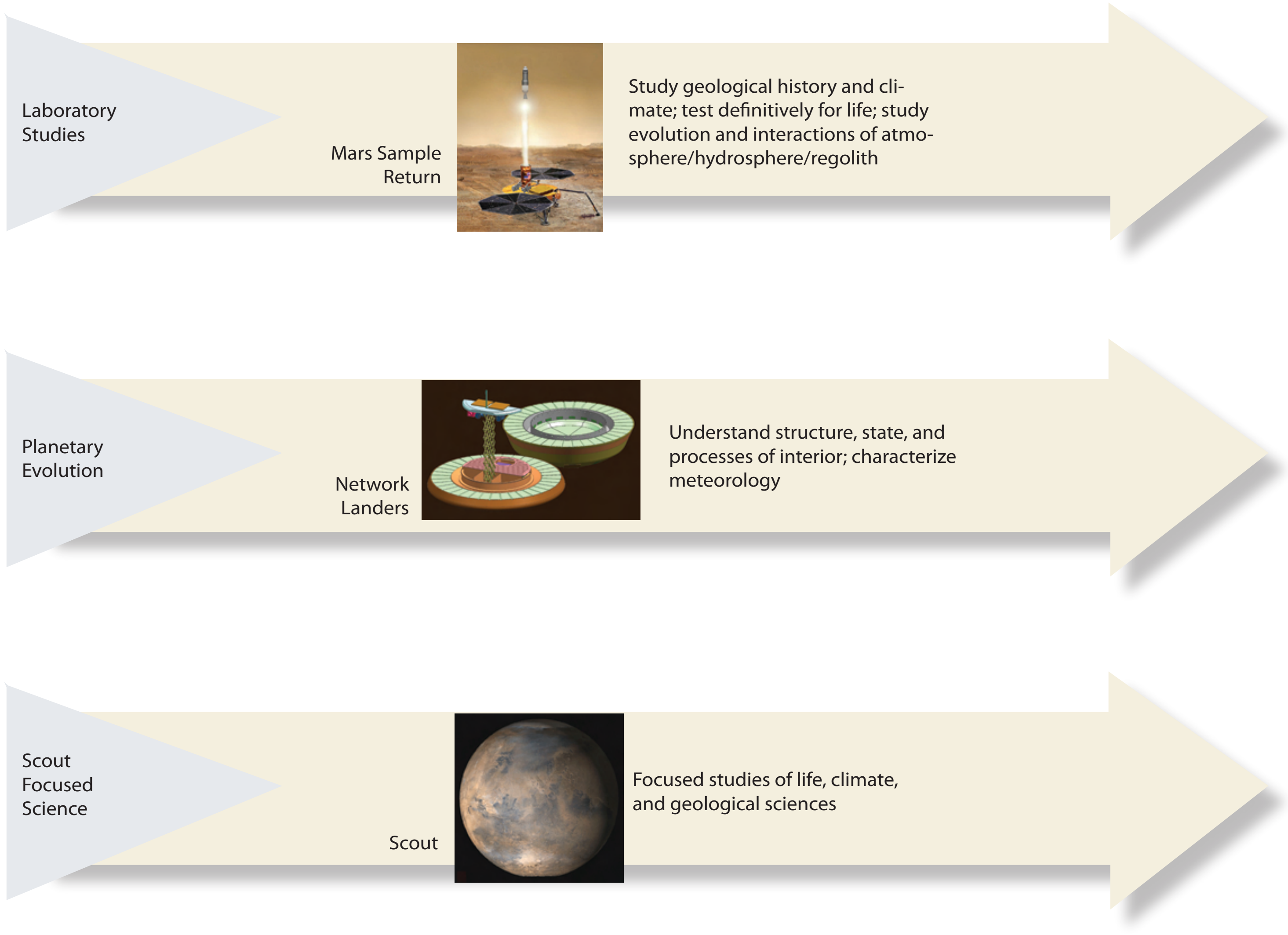


Figure 2b. Mars Program Architecture (Potential Future Missions).



The second option is in 2016 — Figure 2a shows a fork in the investigation path at this point. MAPG intends that the choice of the Astrobiology Field Laboratory or the Mid Rovers be driven by the scientific findings from MRO, Phoenix, and MSL. In the Life goal discussion (see Section 3.1), we indicate that AFL will be the mission of choice for 2016 if findings by earlier missions demonstrate that a habitable site has been identified, capable of preserving organics, and, in the optimum case, organic material and/or biosignatures are detected. If additional searches are needed, the Mid Rover option is preferred in 2016 in which multiple sites are explored for habitability and the presence of organics.

In Figure 2b, we show missions that may launch in 2018 and 2020, depending on the availability of resources (see Section 4.6 for discussion).

2007 Phoenix

The Mars Scout Phoenix mission (Figure 3), scheduled for launch in August 2007, is the first mission selected through the Mars Scout Program. Phoenix is designed to measure volatiles (especially water) and complex organic molecules in the arctic plains of Mars, where the ODY orbiter has discovered evidence of ice-rich soil near the surface. Phoenix is a fixed lander designed to use a robotic arm to dig to the ice layer and analyze samples with a suite of sophisticated on-deck scientific instruments.

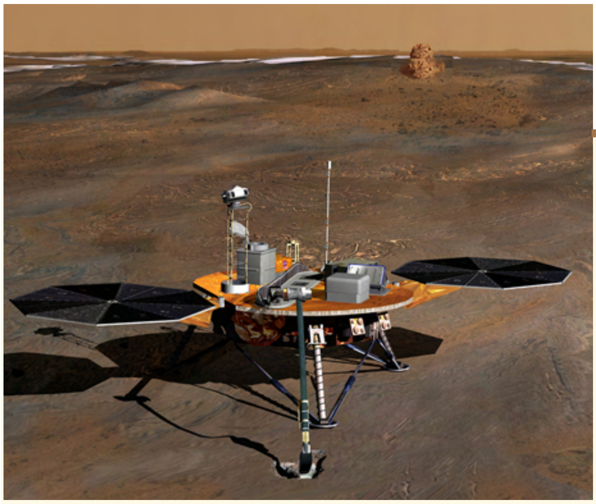


Figure 3. Mars Scout Phoenix.

OBJECTIVES

- Understand the water cycle and its interactions with the atmosphere and the regolith.
- Determine the recent history of water and its role in shaping the surface.
- Determine if the landing site is a habitable zone by looking for organics and other biogenic elements.

PAYLOAD

- Microscopy, Electrochemistry, and Conductivity Analyzer
- Thermal and Evolved Gas Analyzer
- Stereo Camera
- LIDAR
- Meteorology Suite
- Robotic Arm
  - — Camera
  - — Thermal and Electrical Conductivity Probe
- Mars Descent Imager

MISSION

- Launch: August 2007
- Landing: May 2008
- Mission end: September 2008
- Latitude: 65°–72° N

2009 Mars Science Laboratory

MSL (Figure 4) will explore the geochemical, mineralogical, and geological diversity of Mars in search of potential habitable zones. MSL will collect rock and soil samples and analyze them onboard in search of organic compounds and other indicators of previously habitable conditions. MSL will be significantly larger than the Mars Exploration Rovers with the capability to travel longer distances. Additionally, MSL will demonstrate a variety of new technologies including guided entry and a "sky-crane" landing system that will allow for more accurate landing on the surface.

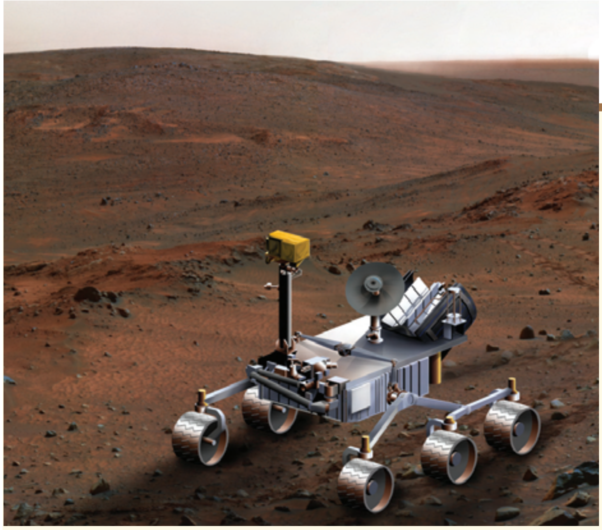


Figure 4. Mars Science Laboratory (design concept).

OBJECTIVES

- Assess biological potential of landing site.
- Characterize geology at all appropriate spatial scales.
- Investigate chemical, isotopic, and mineralogical composition of geological materials.
- Investigate planetary processes that influence habitability.
- Characterize broad spectrum of surface radiation.

PAYLOAD

- Surface Imaging and Atmospheric Opacity
- Chemical Composition Laser and Imaging
- Landing Site Descent Imaging
- Chemical Composition Spectrometer
- Microscopic Imaging
- Gas Chromatograph Mass Spectroscopy and Laser Spectroscopy
- X-ray Diffraction/X-ray Fluorescence
- Pulsed Neutron Source and Detector for measuring hydrogen or ice and water
- Environmental Monitoring Station
- High-Energy Radiation Instrument

MISSION

- Prime mission is one Mars year
- Latitude-independent and long-lived power source, pending approval
- 20 km range
- 75 kg of science payload
- Acquire ~70 samples of rock/regolith
- Large rover, high clearance; greater mobility than Mars Pathfinder or Mars Exploration Rover

2011 Scout

Scouts are novel concepts complementary to the strategic missions. They are focused, and selected by NASA through competitive evaluation.

2013 Mars Science Orbiter

Three priority investigations have been identified for an early orbiter mission: atmospheric evolution, atmospheric trace species characterization (including methane) and fluxes, and shallow subsurface imaging. In addition, MSO (Figure 5) provides missions flown later in this decade with required telecommunications support. The mission requirements for each of the three science areas are well matched to the capabilities of a telecommunications orbiter. The MSO/MEPAG Science Analysis Group has identified atmospheric evolution and trace gases to be the objectives of choice.

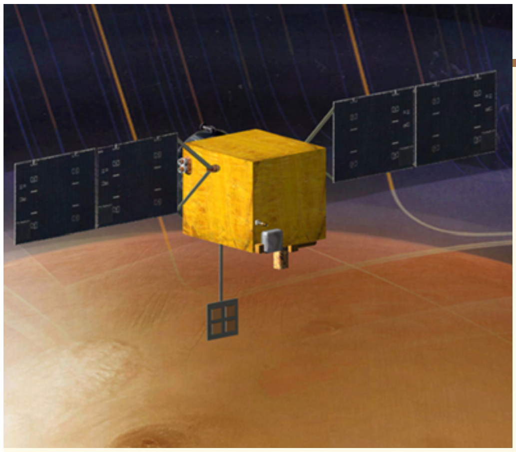


Figure 5. Mars Science Orbiter (design concept).

OBJECTIVES

- Determine interaction of solar wind with Mars
- Determine diurnal and seasonal variations of upper atmosphere and ionosphere
- Determine influence of crustal magnetic field on ionospheric process
- Measure thermal and non-thermal escape rates of atmospheric constituents and estimate evolution of Martian atmosphere

ISSUES

- Science requires orbit to dip into atmosphere (>130 km)
- Planetary protection for low altitude orbiter
- Trades between science and telecom on orbits and phasing of mission objectives

HERITAGE

SPACECRAFT

- Odyssey
- Mars Reconnaissance Orbiter (MRO)

INSTRUMENTS

- Nozomi instruments
- Earth and planetary instruments

TELECOM

- Electra

For 2016, the two options are the Astrobiology Field Laboratory and the Mid Rovers.

2016 Astrobiology Field Laboratory

AFL (Figure 6) will respond to a discovery of biological significance, e.g., organic material. AFL's role is to characterize, in detail, putative biomarkers to determine whether, in fact, there is a connection with prebiotic chemistry or living organisms. AFL is to be a rover, based closely on MSL but with a biology-capable payload and carrying the next-generation sample processing system.

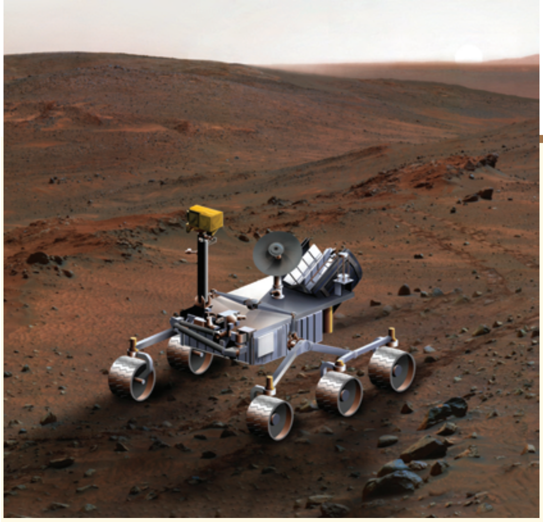


Figure 6. Astrobiology Field Laboratory (design concept).

OBJECTIVES

- Assess biological potential of sites, interpret paleoclimate record, and search for biosignatures of ancient and modern life.

ISSUES

- Viability of mission depends on Mars Science Laboratory (MSL) results in its search for organics
  - Potential for Phoenix to play this role as well
- Planetary protection

HERITAGE

SPACECRAFT AND EDL

- Mars Science Laboratory (MSL)

INSTRUMENTS

- Mars Science Laboratory (MSL)

2016 Mid Rovers

The Mid Rovers (Figure 7) are two MER-derived rovers directed to different sites to explore the geologic diversity on Mars and, perhaps, search for organic material. The sites will be identified as having high scientific interest from Mars Reconnaissance Orbiter observations. The payload elements will be remote and contact instruments.

Figure 7. Mid Rovers (design concept).

OBJECTIVES

- Evaluate the geologic context and detect organics at targets identified by prior missions.

ISSUES

- Implementation goal is two rovers launched for cost of Mars Science Laboratory (MSL)
- Modest yet capable payload
- Minimize landing ellipse (≤ 50 km) and maximize landing altitude (≥1.5 km)

HERITAGE

SPACECRAFT

- Mars Exploration Rover (MER)
- Mars Science Laboratory (MSL)

EDL

- Mars Science Laboratory (MSL)

INSTRUMENTS

- Mars Exploration Rover (MER)
- Mars Science Laboratory (MSL)

4.5 MEPAG Science Analysis Group Review of 2006 Mars Exploration Strategy

The Mars Exploration Program Advisory Group (MEPAG) convened a special Science Analysis Group (SAG) to review the draft program plan — an earlier version of the strategic plan presented above — in light of comments submitted by MEPAG members (at their November 2005 meeting) and after analysis by this SAG. The MEPAG SAG was chartered to provide a report that delineates the strengths and weaknesses of the plan along with possible alternative approaches. The SAG judged the following broad scientific goal and associated objectives as ones scientifically of highest importance and of highest interest to the various stakeholders involved in Mars exploration:

- Program Goal: Understand the Evolution of Mars, the Presence or Absence of Habitable Zones, and If Life Formed or Existed.
- Objectives for the Coming Decade: Follow the Water and Search for Habitable Zones

The SAG believed that each mission is part of the program plan and should be judged against the ability of the mission to meet the above goal and objectives. Based on comments made by community members and analysis by the SAG itself, the SAG determined that the program plan's approach, with four core science investigations augmented by competed Scout missions, is a scientifically robust plan that will meet the above goal and objectives. The primary issues are the relative timing of the missions, the role of Scouts, and consideration of infrastructure.

The SAG found that the approach of a Scout and a core orbiter (focused on aeronomy or trace species) for the 2011 and 2013 opportunities represented a reasonable approach for expected budget profiles and technological readiness issues. The SAG was concerned with how potential conflicts between proposed Scout missions and the core orbiter will be addressed, and suggested that planning for both opportunities proceed in parallel, with the science thrust for the earlier mission impacting the science thrust for the later mission.

The SAG focused the majority of its deliberations on the 2016 opportunity and debated whether the appropriate mission was an in situ investigation (AFL or Mid Rovers), a sample return mission, or a network of landers, as all three meet the program objectives. AFL was determined to be a logical follow-on to MSL to search for regions and materials thought to have supported habitable zones. The Mid Rovers would investigate geologic evolution of multiple locations on Mars suggested by findings from previous orbiters. The SAG endorsed the need for rover capabilities as opposed to static landers. The SAG found either AFL or Mid Rovers to be scientifically compelling and consistent with the program goals and objectives. AFL more directly addresses habitability and life and is preferable if the data lead us to suspect there are key areas for habitable zones and life preservation. The group thought that MSL may appear too late in the cycle to impact a decision between AFL and Mid Rovers. Technology investment for in situ instruments is critical and must be supported.

The swapping in of a Mars Sample Return (MSR) would respond to the NRC's Decadal Survey for Solar System Exploration (Belton et al., 2002), which ranked sample return as the highest priority for large Mars mission. A simple grab by a stationary lander was judged to be inadequate. Cost and reliability of cost estimates were two issues discussed at great length. The SAG concluded costs were fairly well understood and that cost uncertainty should not be an impediment. Technological readiness for the mission is a key issue.

A network mission focused on interior structure, atmosphere, and climate requires strategic mission-level funding (beyond Scout-level) to be completed successfully. The SAG noted that there are more mission options for making atmospheric and perhaps seismic and/or heat flow measurements and recommended that all missions to the surface consider use of EDL measurements to support a "virtual" network. The advantages of bringing a network lander mission forward include addressing the core investigation of interior structure in a more timely and direct fashion.

The SAG found Scout missions encourage the growth of the Mars community and provide greater flexibility of rapid response to discoveries or technological advances. The lower costs of Scout missions assist the program to stay within budget while maximizing launch opportunities. However, the current cost cap will curtail many of the advantages otherwise possible with Scout, and was suggested to be re-addressed.

The SAG suggested the inclusion of an orbiter mission with telecommunications capability in either 2011 or 2013. In addition, to ensure a robust infrastructure plan, the program should strive to maintain redundant on-orbit relay assets by managing the ODY and MRO spacecraft with the goal of significant extended lifetime.

Finally, the SAG noted that Mars Exploration is now an international endeavor and cooperation between space agencies will allow the core missions to be implemented sooner rather than later and at lower cost to any given space agency or country.

4.6 MAPG-Identified Deficiencies in the 2007–2016 Plan

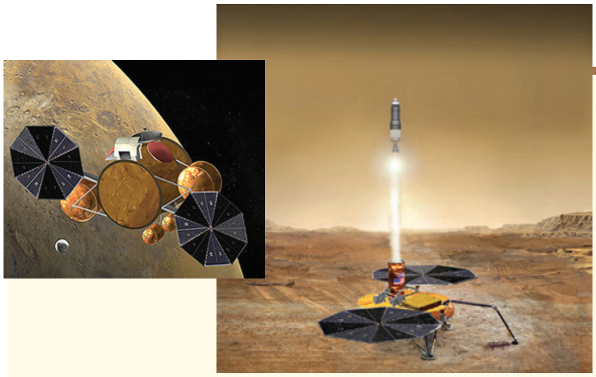
Sample Return

The Mars Exploration plan for the coming decade presented here postpones into the indefinite future the first mission to return samples of rock, soil and atmosphere from Mars. MAPG did not make this decision on scientific grounds. Rather, broadly based scientific support for early MSR is longstanding and firm — the NRC Decadal Survey for Solar System Exploration (Belton et al., 2002) gives MSR its highest priority. However, MAPG was charged with crafting a plan that balanced science requirements with available resources and program priorities.

Sample return from the surface of Mars (Figure 8) is an essential component to understanding the evolution of the planet and its surface, and the program cannot be complete without it. Science instruments aboard robotic spacecraft are inherently limited in terms of mass, power, volume, data rate, schedule, sensitivity, precision, and ability to adapt to unexpected results. In contrast, state-of-the-art analytical instruments operated within Earth laboratories are limited only by technological development. Therefore, return of Martian surface samples is the only means by which some conclusive measurements can be made, depending on the samples returned, such as:

- Precise absolute ages of fundamental Mars crustal units, using multiple radiometric clocks to constrain different kinds of geologic events (current capabilities permit precision of better than 1 Ma on rocks that are 4.5 Ga in age).
- Nature of the interaction between Mars' atmosphere/hydrosphere and the regolith, using ultrahigh-resolution studies of mineral surfaces.
- Evolution of Mars' atmosphere as gleaned from isotope ratios, determined using high-precision gas mass spectrometry.
- Temperatures and chemical evolution of water-deposited chemical sediments, using precise stable isotope studies.
- Ultimate confirmation (or refutation) of the past or present existence of life on the surface of Mars.

Figure 8. Mars Sample Return (design concept).



OBJECTIVES

- Investigate the evolution of the planet and its climate, mineralogy, geochemistry, weathering, and biopotential.
- Mobile sample collection.

ISSUES

- Split launch of Orbiter and Lander
- Early start for technology and MRSH facility
- Relative emphasis on search for evidence of life vs. planetary and climate evolution

HERITAGE

ORBITER

- Mars Reconnaissance Orbiter (MRO)

ROVER

- Mid Rover
- Mars Exploration Rover (MER)

LANDER/EDL

- Mars Science Laboratory (MSL)

Moreover, once samples are in hand, important results can be independently verified, unexpected results can be repeatedly tested using any and all possible supplemental techniques, and portions of all samples can be archived indefinitely to be studied by as-yet undeveloped analytical techniques.

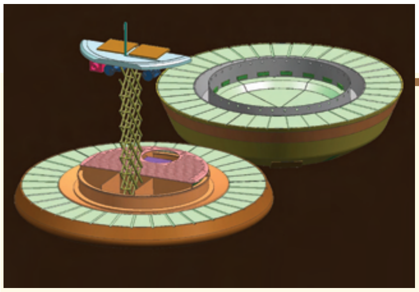
Robotic missions will continue to make exciting discoveries and produce breakthrough findings. Remote and in situ investigations will elucidate the evolution of the planet and its climate, describe the history of water, and, ultimately, determine whether Mars was ever habitable. However, the challenge of substantiating the existence or absence of biological activity on Mars and, if present, fully characterizing it, is too great for in situ investigations alone. Evidence of the truth of this is the ongoing decade-long follow-up investigation of the putative detection of evidence of life in the ALH84001 Martian meteorite. There are other examples. Definitive studies of crustal evolution and the timing and nature of any planetary differentiation depend upon laboratory analysis of samples in laboratories on Earth.

Given the realities of the Mars Program and our conviction that in situ and laboratory analysis are interdependent, we urge that resources continue to be applied to develop the technology needed to enable an MSR mission at the earliest opportunity. This is especially important given the strong interest expressed recently by ESA in a joint NASA–ESA sample return mission.

Geophysics

The 2007–2016 plan for the coming decade of exploration delays, beyond the planning horizon, the investigations needed to advance understanding of Martian geophysics. This is a critical deficiency of the plan because the possible formation of habitable zones at or near the surface of Mars is tied inextricably to the origin and evolution of the planet as a whole. In particular, the bulk composition, differentiation, and thermal/chemical evolution of the interior governed the magnetic dynamo, provided the crustal foundation and basic chemical building blocks, and drove the volcanic and tectonic processes that have shaped the surface and the atmosphere/hydrosphere/cryosphere system through time. For example, the delivery of mantle-derived volatiles to the surface via volcanism is a key factor in the evolution of the atmosphere and water budget. The timing and character of the early dynamo may have played a crucial role in shielding the early atmosphere and surface, providing a conducive environment for prebiotic chemistry. Regional variations in the subsurface thermal environment may modulate the locations and timing of habitable zone development and evolution.

Figure 9. Mars Network Lander (design concept).



OBJECTIVES

- Investigate deep interior (elastic constants, density, interfaces).
- Meteorology and boundary layer dynamics.
- Baseline mission: four landers on ≈1000 km baseline.

ISSUES

- Qualification of rough landers and instruments
- Dispersal of landers
- EDL design
- Number of successful landers required is four

HERITAGE

- Limited in US

INSTRUMENTS

- Substantial Met package heritage
- Substantial US/French development of seismometers

And in a fundamental sense, the interior processes that resulted in the present planet must be understood in order to be able to separate their geochemical patterns from possible subtle chemical biosignatures.

The mission that would carry the instruments capable of performing the essential measurements is a network of at least four static landers (Figure 9). The network would include seismic, heat flow, and planetary rotation measurements at a large number of sites to return fundamental information on the structure and processes of the interior. Without such measurements, we will remain largely ignorant of how Mars evolved as a planet. This network would also include many of the required capabilities for global meteorology.

Meteorology

"Complementary" is a word used repeatedly by MAPG in describing the scientific objectives and measurement platforms for meteorology and geophysics. Both require multiple landed packages operating simultaneously on the surface over a decade or more. However, MAPG was unable, within the constraints, to bring this important integrated mission within our 2016 planning horizon. We note that the mechanisms of climate — the processes that ultimately determine habitability and provide environmental challenges for the future exploration of Mars — must be studied before we can claim to understand Mars.

Some climate processes can be investigated from orbit, but others uniquely require measurements from multiple sites on the surface. These include the mechanisms responsible for surface–atmosphere exchange of heat, momentum, dust, water, and other trace gases. It is not sufficient to simply measure temperature or pressure as has been, and will again be, done by individual landed packages: closure experiments that directly measure fluxes and relate these to environmental forcing factors, including the variation of temperature and wind within the lowest few kilometers of the atmosphere, are required. A network of meteorological stations would provide diurnal and seasonal measurements of these exchange processes and the environment, and provide additional information on the global-to-local scale circulations. This is crucial both for understanding the current atmosphere and inferring ancient climatic conditions, including the time evolution of near subsurface water with direct implications for habitability conditions.

4.7 Future Launch Opportunities to Mars

Table 2 summarizes trajectory performance parameters that may be achieved for Earth to Mars opportunities during the coming decade. These parameters were obtained using various optimization criteria to define representative 20-day launch periods. The data for each opportunity illustrate the performance for both Type I and II trajectories. In some cases, high launch declinations would translate into a degradation of the launch vehicle performance. Additionally, higher achievable latitudes than shown may be reached by paying an extra cost on trajectory performance. These data assume purely ballistic trajectories and should be used for preliminary analyses.

Table 2. Characteristics of Future Launch Opportunities.

	2007	**2009**	**2011**	**2013**	**2016**	**2018**	**2020**
Launch Date	Sep 2007 –Oct 2007	Oct 2009 –Nov 2009	Oct 2011 –Dec 2011	Nov 2013 –Jan 2014	Jan 2016 –Apr 2016	Apr 2018 –May 2018	Jul 2020 –Sep 2020
Arrival Date	Apr 2008 –Oct 2008	May 2010 –Oct 2010	Jul 2012 –Oct 2012	Jul 2014 –Dec 2014	Aug 2016 –Feb 2017	Nov 2018 –Jan 2019	Jan 2021 –Nov 2021
C3 – Launch Energy (km^2/sec^2)	12.7 to 24.7	10.3 to 20.6	8.9 to 12.5	8.8 to 10.2	8.0 to 12.7	7.7 to 11.1	13.2 to 18.4
VHP – V_∞ (km/sec)	2.5 to 4.3	2.5 to 4.7	2.7 to 3.7	3.2 to 5.7	3.7 to 5.7	3.0 to 3.6	2.5 to 4.1
Achievable Latitudes (deg)	84.3 to –89.4	58.2 to –89.3	57.7 to –89.9	74.7 to –85.3	90 to –82.7	78.8 to –81.6	85.1 to –70.3
Season at Arrival	Mid Spring –Mid Summer	Early Summer –Late Summer	Mid Summer– Early Fall	Late Summer– Mid Fall	Early Fall– Mid Winter	Winter	Late Spring –Mid Summer
Probable Dust Storm Activities	~45% of first year	~55% of first year	~60% of first year	~50% of first year	~45% of first year	~25% of first year	~40% of first year

5. Sustaining Elements of the Strategy

5.1 Planetary Protection

It is possible that the 2016 rover mission will explore special regions on Mars (within which Earth or Martian life could propagate) and make measurements intended to search for extant life. In order to preserve the option to implement a mission of this type, it will be necessary to develop the capability to implement the required planetary protection (PP) controls. Depending on the design of the landed system, implementation of the necessary controls could involve sterilization of the landed system and encapsulation of the system in a bioshield to preserve cleanliness until after launch. To prepare for this scientific option, it will be necessary to provide adequate resources for the long lead-time planning and capability development, which would be required in advance of the pertinent 2016 mission planning decisions. The long lead-time items include technologies associated with prelaunch system cleaning and sterilization; flight qualification of parts, materials, and processes; and facilities to accomplish the required planetary protection controls prior to launch.

It is also worth noting that development of planetary protection capabilities in support of the 2016 lander mission will benefit preparation for an eventual MSR mission, where strict planetary protection controls will be required to prevent forward contamination (as for the 2016 mission) and to protect the Earth from back contamination. Specific MSR science objectives will affect planetary protection implementation choices, but the capability to perform system-level sterilization will provide options to enhance programmatic decision-making. (As part of the program plan, it is important to note that planning for an MSR Sample Receiving Facility will still need to begin about 10 years prior to the return of samples.)

The minimum required in the near term is to understand the long-lead planning necessary to support the 2016 rover mission, to carry out that planning at least through the major decision points in the 2009–2011 time frame, and to initiate any facility and technology development that is identified as needing an early start. All such planning will have value to the program in preparation for future life-detection missions and for sample return.

In preparation for future exploration of Mars in search for life, there are two other key areas for investment. One is development of a Mars geographic information system, or equivalent, to support decision processes concerning planetary protection and science site selections. Such a system could be developed using current technology and the growing international data sets for Mars. The other is creation, using modern molecular (or "genomic") techniques, of an inventory of the microbial populations relevant to Mars spacecraft. Such an inventory would lead to a less speculative approach to bioburden controls instead of the highly conservative approach that has been used historically. While planetary protection policy will surely reflect caution for years to come, advances in our knowledge of the relevant biological challenges and in our engineering capability to meet those challenges will benefit the Mars Program as exploration continues.

5.2 Technical Heritage in Coming Decade Missions

Ongoing development of missions in the first decade will net significant advances that will propel mission development in the coming decade. Key examples include:

1. New high-bandwidth (5 Mbits/s), deep space digital communication with high-bandwidth relay capability (MRO).
2. High-resolution (30 cm) surface assessment for safe landing site selection.
3. Precision-guided entry systems that land within 10 km of a designated target (MSL).
4. High payload mass (750 kg) EDL systems (MSL).
5. Long-distance (5–20 km) surface exploration mobility and navigation systems (MER and MSL).
6. Wide area access EDL systems that can land nearly anywhere within ±60 deg latitude and as high as +2 km (MOLA geoid).

Despite these advances, the coming-decade missions will require further technology and system capability developments that will not be achieved by 2007.

For targeted astrobiological surface systems including AFL and MSR, needed key technologies include:

1. Pinpoint EDL to improve and expand landing site accessibility. This capability includes improved descent imaging systems and surface map correlation algorithms that enable surface-relative navigation during descent. These subsystems will also need to be integrated into the terminal guidance system to enable propulsive maneuvering to one or more designated safe targeted sites with less than 100 m error.
2. EDL systems capable of landing higher mass and during the dust season. In the coming decade, landing systems arrive during the southern summer and, therefore, have a larger probability of arrival during or after dust storms that result in degraded entry conditions. In addition, any mission extensions of MSL (e.g., AFL) will require additional payload mass delivery capability. The development of larger (25–30 m diameter) supersonic parachutes has been identified as the highest leverage option to improve payload mass and to counter the adverse effects of high dust loading in the atmosphere.
3. Low-mass drilling systems. Low stowed-volume drilling systems capable of drilling 10 m or more with a mass of less than 50 kg may be required for subsurface access.
4. Spacecraft sterilization methods and dry heat microbial reduction. Flight hardware able to withstand high heat or alternate methods of sterilization will be needed.

For small networked landers, some needed key technologies include:

1. Reliable EDL systems for small networked landers. Low-mass descent and touchdown systems will be needed to deliver 10-kg science payloads to the surface with entry masses less between 200–400 kg.
2. Shock-tolerant seismic and atmosphere science instruments.

New and improved science instruments are crucial for the future missions. MAPG urges NASA to return funding for advanced instrument development to at least pre-2006 levels. The Base Program of the Mars Technology

Program is under extreme fiscal pressure. Gap technologies for future Scout missions are developed via the Base Technology Program, if resources permit, as well as high-risk and high-payoff technologies for all future missions, including the Mars Sample Return mission.

MSL will utilize guided-entry technology to decrease the landing error and Skycrane technology for soft landing. Other new technologies in MSL include sample acquisition via coring, sample processing, long-lived actuators, proposed nuclear power for the rover, several new in situ science instruments, and enhanced ground operations.

The focus of the Technology Program for planned missions will develop required capabilities to Technology Readiness Level (TRL) 6 by the Preliminary Design Review (PDR) of each mission. MSO-focused technology is developing improved proximity communication to increase the data bandwidth for telecom orbiters and cooling technology needed for low-noise IR detection instruments. AFL-focused technology includes precision sample processing for in situ science instruments, planetary protection, and enhancements for rover autonomy in mobility and science operations. Mid Rover–focused technology includes the development of smaller descent engines and enhancements to rover autonomy. Network lander–focused technology includes ruggedizing sensitive subsystems to withstand large forces resulting from high-velocity impacts and the development of a subsonic parachute with drape abatement capability. The focus technology program will also develop two technologies that are required for multiple future missions. These are larger supersonic parachute development and validation to increase the landed mass and landing altitude and pinpoint landing to enable missions to land at locations targeted by science.

5.3 Telecommunications Infrastructure

The Spirit and Opportunity rovers have clearly demonstrated the value of relay telecommunications to enable and enhance Mars surface exploration. The availability of relay links through the ODY and MGS orbiters, each equipped with UHF relay payloads, has benefited rover safety, mobility, and science relative to conventional direct-to-Earth communications:

1. Increased data return — 97% of all of the data acquired from the rovers has been returned via the UHF relays through ODY and MGS.
2. Greatly increased energy efficiency for communications, freeing up scarce rover energy for mobility and in situ data acquisition.
3. Increased communications opportunities, including relay contacts during the Martian night when Earth is not in view.
4. Acquisition of high-rate engineering telemetry during critical events such as EDL.
5. Accurate position determination in the Martian reference frame based on Doppler tracking during relay contacts.

The arrival of the 2005 MRO at Mars, also equipped with a relay payload, will sustain these relay capabilities as MGS approaches the end of its operational life. MRO and ODY will serve as core, redundant, relay assets for the 2007 Phoenix and 2009 MSL missions.

In order to ensure future second-decade landers of these telecommunications benefits, the program plan must address the evolving capabilities and reliability of the Mars relay infrastructure. With the cancellation of the 2009 Mars Telecommunications Orbiter (MTO) — a high-performance, dedicated relay satellite — the program is instead adopting a continuation of the cost-effective strategy of utilizing orbiters that combine science and telecom capabilities in order to provide relay services to future landed missions. The success of this strategy hinges on a combination of long operational lifetimes and sufficiently frequent orbiter launches, in order to sustain redundant on-orbit relay assets, ensuring high confidence in the availability of relay services. Based on this strategy, the proposed program includes the MSO to be launched in either the 2011 or 2013 launch opportunity. This hybrid science/telecom orbiter, coupled with MRO, will establish the core relay infrastructure for robotic exploration through 2016 and beyond. Given the importance of MSO as an infrastructure asset, it will be important to integrate the MEPAG SAG, as well as the future Science Definition Team report, for MSO science goals as soon as possible in order to understand how the mission's science-driven orbit selection will impact relay performance.

While falling short of the performance anticipated for MTO, advances in the relay payload capabilities onboard MRO and MSO will provide for growth in data return, commensurate with the increased needs of future highly capable landers such as MSL and AFL. However, an important consequence of the loss of the high-altitude MTO is the reduced coverage for critical events; this may impose mission design constraints on landed missions to ensure that critical mission events such as EDL occur within the reduced coverage footprint of the lower-altitude science/telecom hybrid orbiters. Should mission anomalies lead to the early loss of MRO and/or MSO, the program may need to examine options for replenishing the on-orbit relay infrastructure, including the possibility of flying a dedicated telesat or, at lower cost, upgrading the cruise stage of a lander mission to allow it to insert into Mars orbit and serve as a long-term relay orbiter.

5.4 International Cooperation

Cooperation among nations in robotic exploration of space is now common. The most recent example is the highly successful Cassini–Huygens mission. For this mission there was a substantial interdependency that benefited both NASA, responsible for the Saturn orbiter, which carried the probe; and ESA, provider of the Titan probe. Payloads on both craft were shared among national space agencies. More often, interdependencies are kept to a minimum — science instruments, selected competitively, are exchanged with little or no cross-agency critical hardware. The most notable exception to the tendency away from independence is the critical support provided by NASA's Deep Space Network for nearly all missions. For Mars, instrument and sensor exchanges are common, yet cooperation on a Mars mission has not reached beyond the level of payload and DSN. The MAPG believes that Mars exploration has transitioned into a class of mission complexity and cost for which interdependence beyond payloads will be an enabling, perhaps required, aspect of future missions.

International cooperation could bring two Mars missions in our plan into better alignment with our science strategy — MSR and the Geophysical and Meteorology Network. MSR has been the subject of detailed study by NASA and CNES as a cooperative mission. In that study of a truly joint mission, NASA was to have provided the outbound spacecraft, sample collection rover, and Mars ascent vehicle. The orbiter that performed the rendezvous with the sample canister was to have been provided by CNES. Returned samples would have been shared.

We strongly encourage NASA to engage in discussions with other space agencies in order to study potential cooperative MSR and network missions. If interest is expressed — this is likely as ESA has announced their intent to perform an MSR in the coming decade — a joint science team to discuss requirements supported by mission engineering would be a most helpful step toward realizing these missions.

6. Summary

MAPG's plan for exploring Mars in the interval 2007–2016 is driven by science, feasible from the perspectives of engineering and technology development, and consistent with NASA's priorities and estimated funding. The plan supports the nation's Vision for Space Exploration by informing NASA about the Martian environment. Human explorers will benefit from this essential information, and risks to hardware will be mitigated. The plan builds upon understanding obtained in the first decade of NASA's return to Mars. The plan is robust to future scientific discovery, and it adopts lessons from prior missions for working near and on Mars.

Program priorities and estimates of the resources available to the Mars program have influenced the plan greatly. We recognize that these are forecasts and subject to change. Consequently, MAPG wishes to encourage NASA's Mars Exploration Program management to return to the Mars community for revisions or new plans as the future unfolds.

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