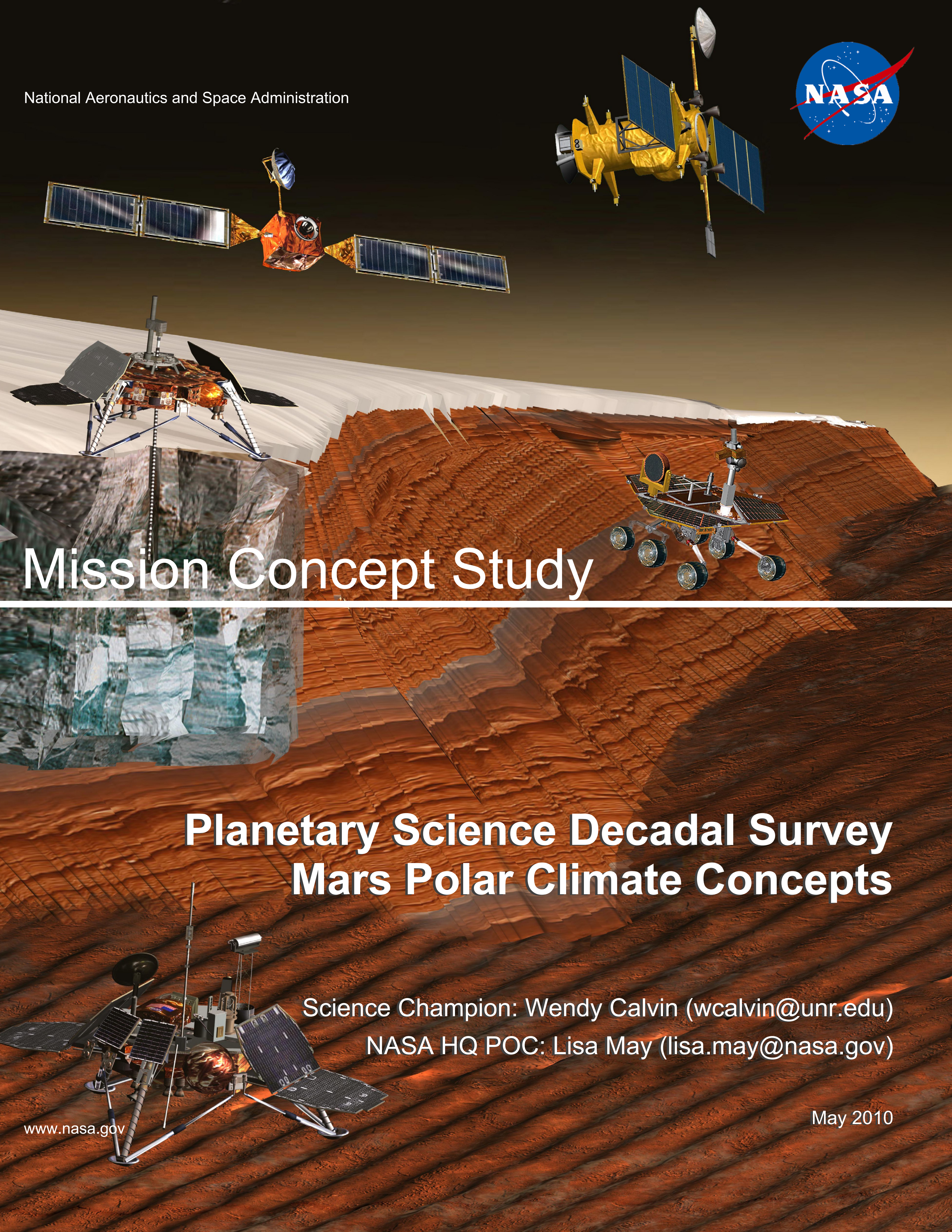

National Aeronautics and Space Administration

Mission Concept Study

Planetary Science Decadal Survey
Mars Polar Climate Concepts

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Data Release, Distribution, and Cost Interpretation Statements

This document is intended to support the SS2012 Planetary Science Decadal Survey.

The data contained in this document may not be modified in any way.

Cost estimates described or summarized in this document were generated as part of a preliminary, first-order cost class identification as part of an early trade space study, are based on analogies to previously flown missions and instruments, and do not constitute a commitment on the part of JPL or Caltech. Costs are rough order of magnitude based on architectural-level input and parametric modeling and should be used for relative comparison purposes only. These costs are not validated for budgetary planning purposes.

Cost reserves for development and operations were included as prescribed by the NASA ground rules for the Planetary Science Decadal Survey. Unadjusted estimate totals and cost reserve allocations would be revised as needed in future more-detailed studies as appropriate for the specific cost-risks for a given mission concept.

Planetary Science Decadal Survey

Mission Concept Study Final Report

Tables

Appendices

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Executive Summary

Architectural survey study sessions were conducted to explore the degree to which science objectives, related to the study of the martian climate via the record preserved in the polar-layered deposits, could be pursued by small (Discovery-class) to moderate (New Frontiers–class) missions.

Five mission concepts were identified during the study, including two orbiters (one Discovery-class with two slightly different instrumentation options and one New Frontiers–class), two stationary landers (one that would likely be on the borderline between Discovery- and New Frontiers–class), and a mobile lander (New Frontiers–class rover). While missions were identified that could make progress against the stated priority objectives and measurements within the Discovery class, missions in the New Frontiers class would make substantially more progress in these areas.

The two more ambitious landed missions would contain sampling systems that could either be based on traditional coring and sample handling systems, or on a heated sample acquisition system. These systems would benefit from additional technology development investment prior to developing formal mission proposals based on these systems. Additionally, all of the landed missions would benefit from precision-guided entry (PGE) to reduce landing accuracy uncertainties; a capability which is currently planned for demonstration via the MSL landing system in 2011 and was considered for the Phoenix mission but descoped due to resource limitations. Airbag landing systems based on Mars Pathfinder (MPF) and the Mars Exploration Rover (MER) (as proposed herein for the rover mission) do not currently have PGE capabilities. Pre-project technology investment in this capability would also help reduce mission costs and cost uncertainty in this area.

For cost estimation purposes, this study assumes that all costs are borne by NASA. However, the team did discuss aspects of the mission concept that could be well suited for international cooperation.

In the interest of completing a study of considerable breadth across multiple mission architectures and of varied complexity, few detailed quantitative assessments were completed as part of this study. However, additional, more detailed, studies of these mission concepts (e.g., Team X studies) are likely to confirm their viability within the proposed mission cost classes.

1. Scientific Objectives

Science Questions and Objectives

Following up on scientific results from the Phoenix (PHX) mission and other general high-latitude ice studies, there is strong community support behind a mission to the exposed polar-layered deposits (PLDs) on Mars. The purpose behind this study is to understand what types of mission architectures could best achieve the primary science goals recently articulated by the Mars polar community [1] and several Decadal Survey white papers. Drilling, roving, and specific orbital observations have been proposed as methods to access the stratigraphy and climate history locked in these deposits. The prioritized science questions of this study are as follows:

1. What is the mechanism of climate change on Mars? How has it shaped the physical characteristics of the PLDs? How does climate change on Mars relate to climate change on Earth? What chronology, compositional variability, and record of climatic change are expressed in the PLDs?
2. How old are the PLDs and how do they evolve? What are their glacial, fluvial, depositional, and erosional histories, and how are they affected by planetary-scale cycles of water, dust, and CO_2?
3. What is the astrobiological potential of the observable water ice deposits? Where is ice sequestered outside the polar regions, and what disequilibrium processes allow it to persist there?
4. What is the mass and energy budget of the PLDs? How have volatiles and dust been exchanged between polar and non-polar reservoirs, and how has this exchange affected the past and present distribution of surface and subsurface ice?

The following set of specific measurement objectives was taken as input to the study as derived from the science questions. The degree to which these measurements are or are not feasible from a given mission observation platform are discussed in Section 2 for each mission concept.

Remote orbital or in-situ measurement objectives:

- Mass, density, and volume of seasonal CO_2 ice in time and space
- Accumulation/ablation rates and monitoring of residual ice
- Determine near-surface wind velocities as a function of season
- Identify dust content of residual ice deposits
- Link present accumulation/ablation to observed stratigraphy
- Identify the stratigraphy of the uppermost few hundred meters to understand recent oscillations in deposition history

In-situ measurement objectives:

- In-situ measurement of grain size, dust content, composition, and extent of layers
- Elemental and isotopic ratios relevant to age (e.g., D/H) and astrobiology (CHNOPS)
- In-situ measurement of pressure, temperature, winds, and thermal inertia at multiple locations with monitoring of seasonal changes in these values
- Constrain porosity, compaction, and thermal inertia
- Morphological, compositional, and physical evidence for glacial flow and/or melting

Remote orbital measurement objectives:

- Identify transport of water in and out of polar regions
- Identify dust transport in and out of polar regions
- Monitor energy exchange during polar night to understand condensation processes

Science Traceability

Table 1-1 provides the linkages between the science objectives, instruments and architectural platforms that were considered in the five mission concepts developed in this concept study. Note that some instruments are assumed on more than one mission concept. Not all of the science objectives or measurement priorities discussed above are addressed in the identified mission concepts

Table 1-1. Science Traceability Matrix

Science Objective	Measurement	Instrument	Target Platform
Mass, density, and volume of seasonal CO_2 ice	Deposit volume and density	High-resolution altimeter	Orbiter
Accumulation/ablation rates	Location, thickness of time-varying frosts	High-resolution altimeter or in-situ meteorological station	Orbiter or lander/rover
Pressure, temperature, winds	Pressure, temperature, winds	Radiometer (microwave or sub-millimeter from orbit) or in-situ meteorological station	Orbiter or nuclear lander/rover
Grain size, dust content, composition and extent of layers	Microscopic imaging (MI)-scale images, composition	MI, short-wave infrared (SWIR), or Raman spectrometer	Lander/rover
Porosity, compaction	MI-scale images, scraper,	MI-scale images and scraper	Lander
Stratigraphy of the uppermost few hundred meters	Centimeter-scale imaging	High-resolution imaging on orbit or in-situ	Orbiter or lander
Elemental and isotopic ratios relevant to age (e.g., D/H) and astrobiology (CHNOPS)	Isotopes, light elements	Tunable diode laser or Raman spectrometer	Lander/rover
Transport of water and dust in and out of polar regions	Imaging, high spectral/spatial resolution atmospheric sounding	Wide-angle imaging, radiometer (microwave or sub-millimeter from orbit) or thermal emissions spectrometer, high spectral/spatial resolution atmospheric sounding	Orbiter
Evidence for glacial flow and/or melting	Morphology, composition,	High-resolution orbital or microscopic in-situ imaging, SWIR or Raman spectrometer	Orbiter or lander/rover
Energy exchange during polar night	Thermal or active NIR/SWIR	Thermal or active near infrared (NIR) / SWIR, in-situ metrology station	Orbiter or lander/rover

This matrix describes the linkages between science objectives and how they are achieved. Note that “Target Platform” identifies the most appropriate observational location to achieve the science for a given mission concept (e.g., requirements on the spacecraft, trajectory, mission architecture, etc.).

2. High-Level Mission Concepts

Overview of Mission Concepts

Based on the science objectives and science measurement priorities provided by the Decadal Survey science champions for the study, the study team conducted two sessions in which the objectives, the candidate instrumentation and measurement approaches, and the most applicable mission host platforms for each measurement were discussed. The study output consists of a set of five mission concepts (two of which have alternate versions, which could have more capable power supply systems) targeted to fit within the expected cost caps for the Discovery and New Frontiers programs. A summary of each of these mission concepts is described in the following paragraphs.

Mission Scenario 1: Discovery-Class Orbiter

Option A: Current Climate/Weather and Seasonal Cap Properties

Strawman payload: Wide-angle weather camera, microwave atmospheric sounder, and multi-beam light detection and ranging (LIDAR) with centimeter-scale vertical resolution

Addresses the following measurement objectives:

- Mass, density, and volume of seasonal CO_2 ice in time and space
- Accumulation/ablation rates and monitoring of residual ice
- Determine near-surface wind velocities as a function of season
- Identify transport of water into and out of polar regions
- Dust transport into and out of polar regions

Option B: Energy Balance and Composition

Strawman payload: Next-generation spectrometer/mineralogy, ~1–5 m ground sample distance (GSD) camera, and active sounder for polar night observations (microwave or LIDAR)

Addresses the following measurement objectives:

- Identify transport of water into and out of polar regions
- Dust transport into and out of polar regions
- Monitor energy exchange during polar night to understand condensation processes
- Identify dust content of residual ice deposits
- Link present accumulation/ablation to observed stratigraphy

Mission Scenario 2: New Frontiers–Class Orbiter

Strawman payload: Next-generation spectrometer/mineralogy, ~1–5 m GSD imagery, wide-angle weather camera, microwave atmospheric sounder, and multi-beam LIDAR with centimeter-scale vertical resolution

Addresses the following measurement objectives:

- Mass, density, and volume of seasonal CO_2 ice in time and space
- Accumulation/ablation rates and monitoring of residual ice
- Determine near-surface wind velocities as a function of season

- Identify transport of water into and out of polar regions
- Dust transport into and out of polar regions
- Monitor energy exchange during polar night to understand condensation processes
- Identify dust content of residual ice deposits
- Link present accumulation/ablation to observed stratigraphy

For all orbiter missions, each can potentially be augmented with detailed gravity mapping of the poles to help characterize the mass distribution across multiple seasons through the use of the existing telecommunications system. Note that the inclusion of a USO for modest cost would facilitate useful radio science observations of the atmosphere in keeping with the overall theme of these particular missions.

Mission Scenario 3: Discovery-Class Stationary Lander: "Sightseer"

Strawman payload: 2-DOF imaging platform with meter-scale imaging spectrometer, centimeter-scale color imager, and meteorological package

Scenario: Land at the base of a PLD stack and interrogate layers optically “from below.”

Addresses the following measurement objectives:

- In-situ measurements of pressure, temperature, and winds
- Morphological, compositional, and physical evidence for glacial flow and/or melting
- Accumulation/ablation rates and monitoring of residual ice
- Determine near-surface wind velocities for a season
- Identify dust content of residual ice deposits
- Link present accumulation/ablation to observed stratigraphy
- Identify the stratigraphy to understand recent oscillations in deposition history

Mission Scenario 4: Discovery/New Frontiers–Class Stationary Lander with Meter-Scale Drill for Subsurface Access

Strawman payload: Subsurface access via melting or percussion drill, sampling of subsurface material (continuous via vapor/tunable diode layer [TDL] or discrete via mass spectrometer), microscopic imager for surface/subsurface, simple color camera, point-spectrometer for surrounding terrain, and meteorological package. Options exist for either a short-lived solar mission or a longer duration advanced stirling radioisotope generator (ASRG) power system.

Scenario: Land at the top of a PLD stack and interrogate layers by sampling them “from above.”

Addresses the following measurement objectives:

- Determine near-surface wind velocities
- Identify dust content of residual ice deposits
- Link present accumulation/ablation to observed stratigraphy
- Identify the stratigraphy of the uppermost meters to understand recent oscillations in deposition history
- In-situ measurements of grain size, dust content, composition, and extent of layers
- Elemental and isotopic ratios relevant to age (e.g., D/H) and astrobiology (CHNOPS)
- In-situ measurements of pressure, temperature, and winds
- Constrain porosity, compaction, and thermal inertia

Mission Scenario 5: New Frontiers–Class Rover with Ice Sampler/Rock Corer

Strawman payload: Mars Astrobiology Explorer-Cacher (MAX-C)-like rock corer, TDL or mass spectometer for isotopes, color imager and spectrometer for terrain monitoring during traverse, MI-class imager for surface/subsurface, and meteorological package. Options exist for either a short-lived solar mission or a longer duration ASRG power system.

Addresses the following measurement objectives:

- Accumulation/ablation rates and monitoring of residual ice
- Determine near-surface wind velocities as a function of season
- Identify dust content of residual ice deposits
- Link present accumulation/ablation to observed stratigraphy
- Identify the stratigraphy of the uppermost centimeters at horizontal scales of hundreds of meters to understand recent oscillations in deposition history
- In-situ measurements of grain size, dust content, composition and extent of layers
- Elemental and isotopic ratios relevant to age (e.g., D/H) and astrobiology (CHNOPS)
- In-situ measurements of pressure, temperature, winds, and thermal inertia at multiple locations with monitoring of seasonal changes in these values
- Constrain porosity, compaction, and thermal inertia

Concept Maturity Level

Table 2-1 summarizes the NASA definitions for concept maturity levels (CMLs). The objective of this study was to develop, to a CML of approximately 2, a number of mission concepts that address the broad science objectives identified. The study team was composed of individuals representing the science, payload and sample acquisition, and overall mission, systems, and programmatic aspects. Rough binning of each mission concept by mission cost class (Discovery or New Frontiers) was conducted by expert/consensus opinion of the participants. Although no detailed quantitative costing analysis was conducted as part of this study, upon more detailed study, most of the missions discussed would likely be proven to have costs in the asserted class (bin).

Table 2-1. Concept Maturity Level Definitions

Concept Maturity Level	Definition	Attributes
CML 6	Final Implementation Concept	Requirements trace and schedule to subsystem level, grassroots cost, V&V approach for key areas
CML 5	Initial Implementation Concept	Detailed science traceability, defined relationships, and dependencies: partnering, heritage, technology, key risks and mitigations, system make/buy
CML 4	Preferred Design Point	Point design to subsystem level mass, power, performance, cost, risk
CML 3	Trade Space	Architectures and objectives trade space evaluated for cost, risk, performance
CML 2	Initial Feasibility	Physics works, ballpark mass and cost
CML 1	Cocktail Napkin	Defined objectives and approaches, basic architecture concept

Technology Maturity

Spacecraft Technologies

Orbiters

Orbiter concepts considered for these missions assume Ka-band telecommunications both on the spacecraft and at the Deep Space Network (DSN) (all stations). While partially demonstrated by the Mars Reconnaissance Orbiter (MRO), this is not a fully developed, operational capability with off-the-shelf hardware (both radios and amplifiers are required). Furthermore, DSN does not currently have Ka-band transmitters or receivers at all stations. Deployment of this capability is scheduled in the future, but if deployment is delayed, this could impact some mission concepts.

Landers/Rovers

All landers considered in this study are likely to require precision-guided entry (PGE) for accurate lander placement. This is driven by the need to ensure lander safety in the polar regions, which might include relatively hazardous environments (from a landing perspective), as well as the need to place the landers as close as possible to the science areas of interest (i.e., escarpments, troughs, etc). Mission durations would be extremely short (90 days or less) thereby limiting the maximum traverse capability to a few kilometers at most. The PGE technology is generally understood and would be demonstrated by the Mars Science Laboratory (MSL) in 2011. However, adapted implementations for specific conditions would be required depending on the lander architecture chosen (Mars Exploration Rover [MER] landers for instance currently have no active control during entry, decent, and landing [EDL]). The development of this type of capability for landing systems smaller than the MSL mission (ideally via a funding source outside of direct mission funds) would be an important element of making the smaller landed missions viable within the Discovery-class cost cap.

Mission scenarios 4 (stationary lander) and 5 (rover) considered herein would gain significant mission-lifetime benefit from using ASRGs as a power system instead of solar, and might even survive throughout a full martian year. This would provide a significant improvement in mission return over solar-powered systems, especially in the arctic polar environments where the stationary lander or rover would spend much of the year with little or no insolation from the Sun. The addition of ASRGs to either the stationary lander or rover concepts would enable direct observation of the polar environment throughout the spring, summer, and fall seasons during which the majority of the atmospheric interaction takes place (springtime melting, cap receding and evaporation, fall condensation, snow and cap growth). ASRGs are not at a flight-readiness level of maturity, however, they are in development. Plutonium is a scarce resource and additional sources are being pursued. Further development and qualification of ASRGs would be required.

Instruments / Payloads

Orbiters

Most payloads identified for orbiting platforms are only minor modifications to existing flight instruments. Therefore, no significant technologies have been identified that would be enabling for the science missions conceived here.

Landers/Rovers

Many of the landed missions considered in this study would require subsurface access. Different mission concepts would require different depths. Many would involve the use of a drill system, which might require 10 cm to 2 m depths (depending on mission). In the mobile case, the rover would traverse to numerous locations on a slope and acquire a sample at 10 cm depth, analyze it, then move on. Technology advancement would be required to ensure no cross-contamination between samples during the sample handling and measurement process. The ability to separate surface/atmosphere constituents from the subsurface material would also be required. Additionally, in order to evaluate larger numbers of samples, drill concepts might be required to use heat / volatilization with a sample path directly to a TDL suite, as opposed to the classical core sampling technique. For the deeper drill concepts, the same volatile method could be employed, allowing continuous instrument sampling with depth. The ability to add drill sections would be required while preserving this capability and limiting contamination. Development of this type of gaseous sampling system for access of icy materials would be an excellent candidate for pre-project development through one of the available technology funding sources such as the Planetary Instrument Definition and Development Program (PIDDP), Mars Instrument Definition and Development Program (MIDDP), Astrobiology Science and Technology for Exploring Planets (ASTEP), or Astrobiology Science and Technology Instrument Development (ASTID).

Key Trades

The following paragraphs provide a discussion of trades, associated with the various architectures, that have been identified for future detailed analysis. These trades were not performed as part of this study nor was any effort made to quantify them. They are merely provided here as a basis for future efforts.

Orbiters

Orbiter concepts should evaluate the trade between additional propellant / fuel for direct placement into the final science orbit versus the cost of ~3 months of operationally intensive aerobraking. Future launch systems will likely have significantly more capacity, which would be required by the missions identified here; therefore, launch mass capability is not a constraint..

Landers/Rovers

For landers/rovers, the following trades should be considered:

- Inclusion of DTE telemetry during the EDL event versus the operational complexity of relay only, including the likelihood that there may only be a single relay asset available during the timeframe of this mission.
- Mobility versus power generation capability.
- Rover - Addition of a simple transmit-only meteorology station on the lander base with better data versus the inclusion on the mobile platform that may not be as accurate or easy to interpret as the data from a stationary base.
- Additional science benefit obtained by operating over a longer seasonal range by inclusion of ASRGs versus the cost of this benefit. This would likely increase the cost of potential Discovery concepts to the degree that they would move into the New Frontiers cost range.
- Launch costs / capabilities versus polar region access.
- Subsurface access versus cost, mass, power and robustness.

3. Technical Overview

Instrument Payload Description

A number of instrument types were identified for use in the missions described in this report. The tables in this section provide the payload options for each mission scenario. For each payload, the study team identified analogous instruments that could achieve the desired measurement as well as the mass and power for each. Whenever possible, instruments with flight heritage were identified. When no analogous instrument existed, estimates were generated via discussions with instrument experts. Note that many instruments are re-used in more than one mission concept.

It should be noted that the power levels quoted for the lander payloads do not include the potential increase due to survival heaters. Since the temperature minimum is less at the poles than at the equator, significant increases in power might be necessary.

Tables 3-1, 3-2, and 3-3 provide the payload for each class of orbiter (mission scenarios 1a, 1b, and 2). Both orbital payloads are straightforward and would enable discoveries at both poles. The assumption for the microwave radiometer included here incorporates the more capable MIRO instrument, allowing for additional target species and data to be acquired. However, it will cost \$5M–\$10M (\$7M–\$15M with reserves) more than the advanced microwave radiometer (AMR) instrument, which is targeted largely at water vapor alone. This is a refinement that can be pursued in more detail at a later date.

Table 3-1. Mission Scenario 1a Payload

Strawman Instrument	Instrument Analog	Mass (kg)	Orbital Avg Power (W)	Daily Data Volume (Mb)
Discovery-Class Orbiter: Option A				
Microwave radiometer	Microwave Instrument for Rosetta Orbiter (MIRO)	19.9	40	200
Wide field-of-view imager	Mars Color Imager (MARCI)	1	5	700
Laser altimeter	Lunar Orbiter Laser Altimeter (LOLA)	12.6	15	600
Totals		**33.5**	**60**	**1500**
For Reference (Mars Odyssey)		**44.5**	**36.3**	**1500**

Table 3-2. Mission Scenario 1b Payload

Strawman Instrument	Instrument Analog	Mass (kg)	Orbital Avg Power (W)	Daily Data Volume (Mb)
Discovery-Class Orbiter: Option B				
Hyperspectral imager	Moon Mineralogy Mapper	8.2	22	200
Medium-resolution Camera	Context Imager (CTX)	3.4	6	1000
Microwave radiometer	Microwave Instrument for Rosetta Orbiter (MIRO)	19.9	40	200
Totals		**31.5**	**68**	**1400**
For Reference (Mars Odyssey)		**44.5**	**36.3**	**1500**

Table 3-3. Mission Scenario 2 Payload

Strawman Instrument	Instrument Analog	Mass (kg)	Orbital Avg Power (W)	Daily Data Volume (Mb)
New Frontiers–Class Orbiter				
Sub-mm radiometer	Microwave Instrument for the Rosetta Orbiter (MIRO)	19.9	59	200
High-resolution imager	HiRISE	65.0	59.7	34,500
Hyperspectral imager	Moon Mineralogy Mapper	8.2	22	400
Wide field-of-view imager	Mars Color Imager (MARCI)	1	5	700
Laser altimeter	LOLA	12.6	31.3	1,200
Totals		**106.7**	**177**	**38,000**
For Reference (Mars Reconnaissance Orbiter)		**139.0**	**137.6**	**37000**

Table 3-4 provides the payload for the Discovery-class stationary lander ("sightseer," mission scenario 3). This package was designed especially for remotely viewing features present in a PLD. In this design, the optical assembly of the SSI would need to be redesigned to have a field of view <1 mrad so that features may be imaged many hundreds of meters away. The hyperspectral imaging spectrometer would be capable of measuring mineralogy through many stratigraphic layers along the PLD. This unit is a version of the M3 imaging spectrometer with a redesigned radiator. The meteorological station analog is the MSL Rover Environmental Monitoring Station (REMS) instrument. REMS measures pressure, temperature, wind speed and direction, relative humidity, and UV flux. The wind measurement is done with six hot plates that can infer wind speed and direction. A more direct measurement could be accomplished by using a sonic anemometer that is in the 3–8 kg payload range. Finally, a mast that could support the REMS sensors and has the point accuracy for the long focal length and hyperspectral imagers is included. The deployment of this mast would have to be done so that the meteorological station would be far enough away from the perturbations due to the lander. Note that substantial additional payload capability is available and the amount of imaging has been maximized to use up 2 passes per sol. It is also possible to add a third or fourth pass per sol (using the excess energy available) to increase the total data volume and acquire more imagery. It might also be beneficial to include contributed payloads or add payloads as funding allows.

Table 3-4. Mission Scenario 3 Payload

Strawman Instrument	Instrument Analog	Mass (kg)	Average Energy (W-hrs)	Daily Data Volume (Mb)
Discovery-Class Stationary Lander: "Sightseer"				
Long focal length imager	SSI (Phoenix)	5.85	150	35
Hyperspectral imager	Mini-Moon Mineralogy Mapper	4.2	220	35
Meteorology	Rover Environmental Monitoring Station (REMS) MSL	1.2	50	0.25
Totals (Note: Power represents maximum values during analysis as not all instruments are on at once)		**11.3**	**420**	**70**
For Reference (Phoenix)		**65.0**	**600**	**70**

Table 3-5 provides the payload for the Discover/New Frontiers–class stationary lander with meter-scale drill and subsurface access (mission scenario 4). Several instruments would be the same as those used in mission scenario 3 (SSI and REMS). The microscopic imager is capable of imaging surface and subsurface samples and is modeled after the MSL Mars Hand Lens Imager (MAHLI) instrument. Similar to mission scenario 3, the hyperspectral imager in this payload would be a complete imaging spectrometer based on the Moon Mineralogy Mapper (M3), although a de-scope to a point spectrometer might be justified if cost or mass dictate. The tunable laser spectrometer (TLS) (or mass spectrometer) would have to be designed to work in conjunction with the drill, and have volatile material fed directly from the bore hole into the cavity for analysis of volatile components of subsurface material. The only analysis of subsurface samples would be in the volatile component, which would be accomplished by mating the TLS to the drill stem so that volatile material released upon contact (H_2O, CH_4, NH_3, etc.) could be directly detected by the TLS. This instrument would also be able to measure isotopic ratios such as D/H $^{12}C/^{13}C/^{14}C$. Finally, the meteorological package would have to be deployed in such a manner as to minimize perturbing effects caused by the lander and its various heat sources. The drill itself is based on the Phoenix arm, which is the best flight analogy currently available. A 2 meter drill capable of accessing the surface from an elevated platform is feasible and would be in the 10–15 kg range. It would most likely require significant power. Payload operations on this platform would be power limited.

Table 3-5. Mission Scenario 4 Payload

Strawman Instruments	Instrument Analog	Mass (kg)	Average Energy (W-hrs)	Daily Data Volume (Mb)
Discovery/New Frontier–Class Stationary Lander with Meter-Scale Drill/Subsurface Access				
Imager	SSI (Phoenix)	5.9	50	25
Microscopic imager	Mars Hand Lens Imager (MAHLI)	1.0	40	10
Hyperspectral imager	Mini-Moon Mineralogy Mapper	4.2	110	18
Tunable laser spectrometer	TLS (MSL)	4.5	80	2
Meteorology	REMS (MSL)	1.2	50	0.25
Drill	Phoenix arm	14.4	300	4
Totals (Note: energy represents average usage with a canonical operation mode)		**31.2**	**630**	**59**
For Reference (Phoenix)		**65.0**	**600**	**70**

Table 3-6 provides the payload for the New Frontiers–class rover (mission scenario 5). This payload is a less capable payload when compared with the sampling capabilities in mission scenario 4. This represents the trade between capability of the payload versus platform mobility. In this scenario, the payload would have an instrumented arm with a drill based on those proposed for the 2018 MAX-C rover. This drill would be used in conjunction with the TLS to measure the subsurface volatile composition. Traversing would utilize almost the entire payload energy and would be limited to the same daily values (~200 W-hrs). This payload mass is still significantly in excess of the lander baseline capability and might require additional descope or lander enhancements to close.

Table 3-6. Mission Scenario 5 Payload

Strawman Instruments	Instrument Analog	Mass (kg)	Average Energy (W-hrs)	Daily Data Volume (Mb)
New Frontiers–Class Rover with Ice Sampler/Rock Corer				
Miscroscopic imager	Microscopic Imager (MER)	0.3	40	10
Meteorology	REMS (MSL)	1.2	50	0.25
Tunable laser spectrometer	TLS (MSL)	4.5	50	5
Arm/drill	MAX-C	15.0	60	8
Totals (Note: energy represents average usage with a canonical operation mode)		**21**	**200**	**23**
For Reference (MER, not including mast and arm)		**9.9**	**200**	**70**

Flight System

Primary Architectures Considered

Five primary architectures were considered in this study, with two alternate concepts provided for possible evaluation of landed missions.

The five primary architectures can be categorized into two classes: orbiter platforms and lander/rover platforms.

Orbiter Platforms

The orbiter concepts were essentially bifurcated into two mission classes: two smaller Discovery-class versions (based on 2001 Mars Odyssey [ODY]) and a larger more capable New Frontiers–class version (based on MRO).

The Discovery/ODY-class orbiter (mission scenario 1a and 1b) would be a ~800 kg spacecraft at launch, hosting approximately 50 kg of payload and providing approximately 100 W orbital average power (OAP) to the payload. This orbiter would use a <2 m high-gain antenna (HGA) and could deliver approximately 2 Gb per day of total data volume (Ka-band system with 10 W transmitter to 34 m DSN). This would be a general-purpose mapping mission, largely focused on polar regions and operating from a polar orbit. Pointing would be sufficient but would not be very high precision (unable to support very high resolution imagers).

The New Frontiers/MRO-class orbiter (mission scenario 2) would be a ~2300 kg spacecraft at launch, hosting approximately 120 kg of payload and providing approximately 150–200 W orbital average power (OAP) to the payload. This platform could achieve high-precision pointing and would be applicable to very high-resolution optical systems such as the High Resolution Imaging Science Experiment (HiRISE). This platform would utilize a large HGA (3 m class) and could provide approximately 25 Gb per day of data volume (Ka-band with 50 W transmitter to 34 m DSN). This platform would also be a polar-orbiting mission performing detailed observation of the northern and southern polar caps, with additional global access as resources allow.

Both orbiter concepts assume aerobraking after initial orbit insertion at Mars, but this should be evaluated (see Key Trades in Section 2). Orbiters would be placed into a Sun-synchronous polar orbit at an altitude optimized for their respective instrument suite, target access, and mission lifetime, likely to be between 250 km and 450 km.

Both orbiter concepts also assume the requirement to host an ultra-high frequency (UHF) relay package as part of the Mars relay network infrastructure (that payload being government-furnished equipment [GFE]). Mission lifetimes assumed for both orbiters are in excess of 5 Earth years (2+ martian years).

Lander/Rover Platforms

Lander concepts were also bifurcated into two main classes: stationary and rover. Both stationary lander concepts are based on the propulsive-descent Phoenix-style lander and the rover version is based on the airbag-landed MER rover.

The stationary lander assumes a largely build-to-print Phoenix-style propulsive lander with some changes. The propulsive lander has the ability to host at least 65 kg of instrument payload and can provide over 600 W-hr of payload energy per sol. The instrument deck on the lander sits approximately 1 m off the surface and is approximately 2 m across, allowing it to host articulating mechanisms up to almost 2 m in length (per segment). The lander could be positioned on the surface during touchdown such that the solar arrays are aligned in an optimal fashion (southward). If required for power reasons, a trade could be evaluated that would add a 1-axis gimbal to the arrays allowing peak power tracking throughout the day. This lander platform would require an avionics upgrade as the previous RAD6K and vintage avionics are no longer available. It is likely that the power requirements would increase slightly for the new RAD750-based avionics suite (baseline assumes JUNO/MAVEN avionics), but this would be balanced by slightly better performing solar cells available in this mission timeframe.

The lander is designed for two UHF passes per sol (limited by energy balance) and would utilize the best two passes per sol from the available relay orbiters. For this study, it is assumed that approximately 35 Mb per pass could be guaranteed (70 Mb per sol total), with some days significantly higher. Additional passes can be utilized should sufficient energy be available.

The propulsive lander has the capability to perform PGE during EDL, reducing the landing ellipse size significantly (some reduction could also be achieved through steeper entry angles but with a commensurate reduction on timeline). This capability was not demonstrated on the Phoenix mission due to technical issues and cost limitations. Some challenges exist with thruster efficacy during the hypersonic portion of the re-entry phase where this technique would be used. Additional effort would be required here to execute PGE. If this lander is used for southern polar missions, additional EDL modifications might be required to achieve the higher landing altitudes present in these target locations.

The stationary lander concept is further bifurcated into an imaging concept (mission scenario 3) and a subsurface concept (mission scenario 4). The imaging concept considers the ability of a lander with a 2-axis gimbaled high-resolution imaging system mounted on a deployed mast, including a multi/hyperspectral imager, to observe the stratification present in the PLDs as exposed on slopes, escarpments, or cliffs within range of the lander. The high-resolution imager would allow centimeter-level resolution within these layers and material identification through spectroscopy.

The subsurface concept would utilize a drill, probe (heated or not), or a robotic arm to access the non-atmospheric affected material layers. Depending on the instrument package chosen to analyze the samples once acquired, the appropriate accessibility tool would be identified. The drill concepts considered include a low-heat, low-damage core driller that would supply samples to a thermal and evolved gas analyzer (TEGA)-like instrument, and a higher heat, mechanical pulverizer that would extract volatiles into a TDL-type instrument directly. The latter is the most straightforward and cost-effective approach and is applied here. Planetary protection requirements would be increased for a lander designed to access the subsurface, taking the standard lander category from IV-A to IV-C (IV-C is a combination of IV-A and IV-B where IV-B reflects the higher cleanliness level for the access device in particular and must be maintained at this higher level when packaged onto the IV-A spacecraft, thus requiring a biobarrier of some form).

Both stationary lander concepts would include a meteorological package and opacity measurements would likely be performed by one of the onboard imaging systems (this would require further evaluation). This platform would have significant payload capacity and would be more likely constrained by cost than by mass or power. In that light, it would be highly beneficial to solicit international contributions. These contributions might include drill systems from the European Space Agency (ESA) (developed for ExoMars), robotic arms from Canada (offered originally for PHX and resulting from their extensive robotic arm experience on the shuttle / International Space Station [ISS]), meteorological systems, optical microscopes, or other atmospheric sensors.

The design of the mobile lander (mission scenario 5) is based directly on the medium-sized MER rover. This rover design has limited power-generating capacity and significantly less payload capacity (in both mass and volume). Hosted payload mass capability would likely be ~10 kg. Packaging might be difficult depending on the payload concept. The rover would generate on average approximately 600 W-hr per sol of which approximately 150–200 W-hrs would likely be available to payload operations or mobility. This platform would require an avionics upgrade from the no-longer-available RAD6K series of flight processing units (FPUs). Further studies should evaluate the applicability of the MSL avionics to this smaller platform.

Similar to the stationary lander, it is assumed that approximately 70 Mb/sol data throughput would be achievable. This platform as currently designed includes DTE communications, but this should be re-evaluated for the mission concepts proposed here.

The MER EDL system has no active control features that would facilitate PGE. This would require potentially significant design changes to implement and would be a major cost risk for this approach. Furthermore, due to the high g's experienced by this landing system, payloads would need to be designed accordingly (and some might not be amenable to this at all).

Demonstrated MER mobility suggests an average traverse rate of approximately 10 mm/s or 36 m/hour. This includes the typical Navcam/Hazcam observations and corrections, path planning, etc. Maximum daily traverse distances should assume 100 m as the upper limit (power constrained). Given a total expected mission duration of 90 sols or less, the maximum accessible range for the mission would likely be in the ~2–3 km range.

The subsurface analyzer would include a drill mechanism that would allow access to approximately 10 cm depth. This would be performed by a drill hosted on the front of the rover (within image access range of the engineering cameras) likely stowed over the top during cruise/EDL and deployed. It is expected that the inclusion of a drill system and requisite sample analyzers would comprise the extent of the platform capability, requiring the removal of the stereoscopic imager. This system would be highly focused on subsurface sample acquisition and evaluation with the mobile platform providing spatial separation between samples either upslope or downslope in the polar terrain, thereby accessing different geologic deposition layers. It is possible that a spectrometer mounted with a nadir-look angle might also be included that would obtain regular samples as the rover traverses, should mass, power, data volume, and costs allow.

Due to the limited solar array area provided in this concept, operations would be fundamentally limited and some amount of time would be required for battery recharging per sol (hence, the traverse limits identified earlier).

All lander missions investigated here would experience a relatively short operational lifetime, driven by the landing latitudes desired (>80 degrees). Due to the high latitudes, the sun would be present almost continuously during the peak of the martian summer, but would rapidly drop in exposure as the season progresses, to the point where the lander would not see sunlight at all. This environment is further challenged by the growth of the polar cap itself, which would potentially fully encase or envelop the lander as CO_2 and water condense and the cap grows. Missions of this type should target arrival dates as close to the beginning of northern (or southern) summer as possible in order to extend this operational period. For the purpose of this study, landed missions are assumed to last no more than 90 sols.

One option that was briefly considered as an augmentation to all of the lander concepts was the inclusion of an ASRG to replace the solar power system. The inclusion of an ASRG would allow the mission to open the launch and arrival space for the polar targets, as well as extend the useful life of the lander beyond merely the middle summer months. This extension would enable meteorology data collection over a span of seasonal variation not otherwise achievable. Additional continuous power capacity would also extend the traverse range of the mobile lander, would add the ability to increase the number of communications passes and thus increase total returned data volume, and might also supplement the system thermal design reducing the total power required to maintain the electronics above their minimum survival temperatures. The addition of an ASRG would also add significant cost not only in the acquisition, testing, and verification of the ASRG itself, but would also add significant launch costs and planetary protection costs. Any potential Discovery-class mission would likely be pushed beyond the

Discovery limits and into the New Frontiers class for cost reasons. Furthermore, analysis is required to establish how useful the added payload operations would truly be if the lander is in a perpetual nighttime condition where lighting conditions might preclude imaging or restrict some payload operations. Rover traversing might also not be possible under low light conditions.

Concept of Operations and Mission Design

Although a detailed consideration of the concept of operations for these missions was not undertaken as part of this study, several general observations can be made regarding the nature of their operations based on similar missions executed in the past.

It can be reasonably expected that orbiter missions could be conducted similarly to ongoing and planned Mars orbiter missions operating in low, circular orbits such as ODY and MRO. Typical cruise, orbit insertion, and aerobraking phases can be expected prior to the initiation of science operations in the mapping orbit, with DSN tracking varying from continuous around critical events (such as launch, orbit insertion, and aerobraking) to between daily and weekly (two to three passes per week) for the rest of the cruise depending on the maneuver schedule.

In the mapping orbit, daily downlinks with daily payload command opportunities are assumed and planned bus uplinks (primarily stored sequences) are assumed to occur one to two times per week. Onboard storage should be sized to allow higher data rate acquisition by the orbiter during the period of each orbit when the pole is in view, and lower data rates at other points in the orbit.

Similar to the orbiters, lander tracking prior to the start of the surface mission can be assumed to vary from continuous around critical events (such as launch, approach, and EDL) to between daily and weekly (two to three passes per week) for the rest of the cruise depending on the maneuver schedule.

Once landed, the two stationary missions would likely have somewhat similar initial operations on the surface of Mars. Command and telemetry sessions through the onboard UHF system would be the most energy efficient and can be expected to occur at least twice per day.

The operations strategy for the mobile system is significantly different than the lander strategy and even differs somewhat from the MER approach. The utility of this mobile system is to access different layers of material as the rover traverses upslope or downslope across layer transitions. Based on variations in optical properties observed from orbit, many layers manifest changes over the scale of 1 meter or less. Through the mission, the rover can be expected to operate in one of two modes: fine sampling during which limited traverses would be completed between samples (on the scale of the layer thickness) and long-duration sampling where the rover would traverse a pre-specified interval between samples (e.g., 10, 20, 50, or 70 meters). Given the amount of time anticipated to acquire and analyze a sample, sampling more frequently than once or twice per day might not be feasible regardless of the distance between sample sites. As the rover traverses from site to site, additional imaging systems (such as microscopic imagers to interrogate variations in grain size or spectrometers to measure changes in mineralogy) could acquire data on the ground below the rover during the traverse.

Landed missions would target polar sites above 80 degrees (N or S). As a general rule, the northern sites are at a lower elevation than the southern sites, providing EDL margins. The northern polar cap has also been identified to contain more water ice than the southern cap, and thus is also more desirable from a science perspective. Dedicated trajectory analysis was not performed for this study; however, some existing trajectory information exists through alternate studies performed through the Mars Program, especially for Mars Sample Return mission concepts [2]. Reviewing the results of these trajectory analyses identifies limited northern polar access over the next decade. There are narrow windows of opportunity to reach >80N latitude for the 2018 and 2020 periods with a very small window (a few days) in the 2022 and 2024 period. These were minimum C3 projections, however (launch mass capability >4500 kg), and were given the reduced mass requirements likely for the PHX- or MER-based landers (~1000 kg and 2500 kg, respectively, versus the much heavier MSR concepts). It is likely that more opportunities will be available with increased launch C3, with the limit becoming entry velocities at Mars. Future more detailed studies should evaluate actual polar access options with the mass estimates reflecting these missions and using the appropriate constraints (i.e., arrival time / season, entry velocity).

Planetary Protection

The two orbiters and the lander mission concept, which would not acquire subsurface ice samples, can be thought of as having typical planetary protection considerations for missions of their class (Category III and Category IV-A, respectively). The stationary lander mission concept and mobile mission concept, which would acquire subsurface ice samples, must be thought of as penetrating a “special region” in a manner that has the potential to cause liquid water to be present and, as such, is expected to be categorized as IV-C (combination of IV-A lander with IV-B access system). The potential presence of an ASRG power system on these two missions would additionally add to the mission complexity and planetary protection cleanliness requirements, up to and including the requirement that the entire lander comply with IV-B levels.

Risk List

A detailed consideration of mission risks was not undertaken as part of this study.

4. Development Schedule and Schedule Constraints

Development Schedule and Constraints

The nature of these mission studies was not tied to a particular launch opportunity or a specific timeframe. However, it was noted that limited Type I/Type II trajectories within the coming decade capable of easily reaching the martian northern polar layered deposits (NPLDs) would be available, some of which would not meet the standard 20-day launch period. Additionally, the lander missions are based on the assumption that adequate relay orbiters would be available to return the data volume generated. Should changes occur to the available assets at Mars during the period evaluated in this study, viability of these mission concepts would need to be revisited.

Apart from this, no other constraints were identified that would pose a challenge to development within the period typically allotted for a Discovery- or New Frontiers–class mission.

Technology Development Plan

Technologies required by or beneficial to these mission concepts are described in Section 2. As these missions are presumed to be targeted for selection/funding via one of the competed proposal processes, selection might be contingent upon mission advocates securing separate funding for the development of these technologies to TRL 6 prior to Preliminary Design Review of the mission being proposed.

5. Mission Life-Cycle Cost

Costing Methodology and Basis of Estimate

Rough binning of each mission concept by mission cost class (Discovery or New Frontiers) was conducted by expert/consensus opinion of the participants. Although no detailed quantitative costing analysis was conducted as part of this study, first order estimates were generated in concert with other studies recently conducted or underway, or by analogy with actual mission costs. Sufficient rigor and assumptions were applied such that upon more detailed study, most of these mission concepts should prove to be within the proposed mission cost classes.

For the purpose of the study, it was assumed that the Discovery cost limit in $FY2015 was $666M and for New Frontiers it was $1.05B (Table 5-1). This is based on the current calls in $FY2010 inclusive of LV costs and inflated to $FY2015.

Table 5-2 provides rough cost assessments for each mission option, following the decadal guidelines requiring 50% reserve on development costs and 25% on phase E costs. Note that an additional $30M cost was included for planetary protection measures for the two subsurface access missions.

Table 5-1. Cost Cap Assumptions

	Discovery		**New Frontiers**	
	$FY2010	**$FY2015**	**$FY2009**	**$FY2015**
Current limit	$425M	$488M	$680M	$793M
LV cost (per SEDS guidelines)	Assumes Atlas V 401		Assumes Atlas V 551	
	$155M	$178M	$220M	$257M
Total Mission Cost	**$580M**	**$666M**	**$900M**	**$1049M**

Table 5-2. Rough Order of Magnitude Mission Cost Assessment

(With 50% Reserves on Development and 25% on Operations [NASA Ground Rules])

	Mission 1a	**Mission 1b**	**Mission 2**	**Mission 3**	**Mission 4**	**Mission 5**
	ODY Class—Climate and Weather	**ODY Class—Energy Balance & Composition**	**MRO Class—Polar Science**	**PHX Class—"Sightseer"**	**PHX Class—Subsurface Sampler**	**MER Class—Mobile Laboratory**
PM/SE/MA	$44M	$45M	$59M	$52M	$86M	$97M
Flight System	$150M	$150M	$250M	$265M	$265M	$400M
Payload	$55M	$65M	$100M	$40M	$75M	$50M
MOS/GDS	$50M	$50M	$60M	$30M	$35M	$40M
Launch (A-401)	$180M	$180M	$180M	$180M	$180M	$180M
Reserve	$134M	$140M	$217M	$184M	$220M	$282M
Mission Total	**$613M**	**$629M**	**$866M**	**$751M**	**$860M**	**$1049M**

Note: Blue indicates within Discovery limits; purple indicates within New Frontiers limits.

Appendix A. Acronyms

AMR	Advanced Microwave Radiometer (OSTM)
ASRG	advanced stirling radioisotope generators
ASTEP	Astrobiology Science and Technology for Exploring Planets
ASTID	Astrobiology Science and Technology Instrument Development
BOL	beginning of life
CBE	current best estimate
CHNOPS	carbon, hydrogen, nitrogen, oxygen, phosphorous, sulfur
CML	concept maturity level
CTX	Context Imager
D/H	deuterium/hydrogen
DOF	degrees of freedom
DSN	Deep Space Network
DTE	direct-to-Earth
EDL	entry, decent, and landing
EOL	end of life
EPS	electrical power subsystem
ESA	European Space Agency
FY	fiscal year
GCMS	gas chromatograph mass spectrometer
GDS	ground data system
GFE	government-furnished equipment
GSD	ground sample distance
HGA	high-gain antenna
HiRISE	High Resolution Imaging Science Experiment
ISS	International Space Station
JPL	Jet Propulsion Laboratory
LIDAR	light detection and ranging
LOLA	Lunar Orbiter Laser Altimeter
LV	launch vehicle
MA	mission assurance
MAHLI	Mars Hand Lens Imager
MARCI	Mars Color Imager
MAX-C	Mars Astrobiology Explorer-Cacher
MEL	master equipment list
MEV	maximum expected value
MER	Mars Exploration Rover
MET	meteorological instrumentation
MI	microscopic imaging
MIDDP	Mars Instrument Definition and Development Program
MIRO	Microwave Instrument for the Rosetta Orbiter
MOS	mission operations system
MPF	Mars Pathfinder
MRO	Mars Reconnaissance Orbiter
MSL	Mars Science Laboratory
NIR	near infrared
NPLD	northern polar layered deposits
NRC	National Research Council
OAP	orbital average power
ODY	2001 Mars Odyssey
OSTM	Ocean Surface Topography Mission
PGE	precision-guided entry
PHX	Phoenix
PIDDP	Planetary Instrument Definition and Development Program
PLD	polar layered deposit
PM	project management
REMS	Rover Environmental Monitoring Station
SAD	subsurface access device
SAM	Sample Analysis at Mars instrument (MSL mission)
SE	System Engineering

SEDS	Solar System Exploration Decadal Survey
SWIR	short-wave infrared
TDL	tunable diode layer
TEGA	thermal and evolved gas analyzer
TES	Thermal Emission Spectrometer
TLS	Tunable Laser Spectrometer
UHF	ultra-high frequency

Appendix B. References

[1] Fishbaugh, K., et al. "Introduction to the 4th Mars Polar Science and Exploration Conference Special Issue: Five Top Questions in Mars Polar Science," *Icarus* 196, 305–317, 2008.

[2] Fernando, Abilleira. 27 February 2007. *Mars Mission Opportunity Design Data Handbook, 2010–2020*. Release 1.8. JPL D-32965.