Mars Concurrent Exploration Science Analysis Group (MCE-SAG) Final Report

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Executive Summary

This report presents the findings of the Mars Concurrent Exploration Science Analysis Group (MCE-SAG), chartered by the Mars Exploration Program Analysis Group (MEPAG) to express community consensus on the highest priority science that should be conducted in parallel with the Mars Sample Return (MSR) program, with a focus on what can be addressed under a low-cost mission model (where low-cost is considered to go up to, and include, the Discovery cost cap of ~$500M[1]). Results from this SAG can be used to help develop a Mars program architecture to begin regularly competing and flying lower-cost Mars missions in the next decade (2023-2032).

The MCE-SAG activities commenced in June 2022, in part as a response to the Planetary Science and Astrobiology Decadal Survey, *Origins, Worlds and Life*. Guidance from the Decadal Survey included the following, "The [Mars Exploration] program should develop and execute a comprehensive architecture of missions…to enable continued scientific discovery at Mars." The results of the SAG activities have been structured to demonstrate the viability of one potential architecture—one that focuses on making opportunities available to low-cost missions to fly concurrently with MSR development.

Under its MEPAG-developed charter, there were four tasks for the MCE-SAG to address:

1. Identify high-priority science objectives, traceable to community documents, that are achievable in parallel with MSR.
2. Assay these objectives to identify constituent parts that are executable as stand-alone investigations that contribute to a broader Mars science program.
3. Determine how such investigations might be addressed within a low-cost mission program within the next decade (2023-2032).
4. Determine what technology development and Mars infrastructure will be needed to support these low-cost missions.

Within the Decadal Survey, principal areas of ice science, life detection, and modern habitability were identified, as well as the importance of linkages to the Moon-to-Mars program and future human exploration; these directions have been incorporated into the SAG assessment. Through weekly meetings and input from external experts, the SAG has identified five top-level science objectives or 'tracks' that will address the highest priority Mars science:

- **Planetary Evolution:** Characterize the geodynamic, petrologic, thermal, and tectonic evolution of the crust and interior of Mars from the pre-Noachian through the present day.
- **Early Environmental Change:** Understand the processes that drove habitability and climate change on early Mars as recorded in the ancient stratigraphic record.
- **Recent Climate Evolution:** Understand modern volatile transport and the drivers of recent climate change using ice records and atmospheric reservoirs.
- **Dynamic Modern Environments:** Understand processes responsible for the modern surface and atmospheric environments by characterizing meteorology, atmospheric fluxes, and other dynamic processes on Mars.
- **Modern Habitability:** Search for currently or recently habitable environments and present-day life on Mars.

[1] as of 2023.

Collectively, these objectives fall under a single, overarching programmatic theme:

***Dynamic Mars**: Investigating ancient and modern drivers of change on an active planet.*

Each objective includes a series of investigations to address the broader science of the objective. These investigations trace to foundational community documents like the MEPAG Goals document and are prioritized within each objective as a means of characterizing their relative science impact. In addition, each investigation has been assayed for implementation feasibility by one or more low-cost missions or mission elements in the next ~10 years. Initial feasibility assessed whether such an investigation could likely be performed 'now,' within five years, or beyond five years.

Once evaluated across these two dimensions—science priority and feasibility—representative mission concepts were established that could conduct each investigation, leading to an interconnected series of notional low-cost missions that could be flown under the overarching theme of 'Dynamic Mars'. The linkages between these example mission concepts, both within and across the five tracks, have been dubbed the 'Braided River', and are designed to emphasize the capability of multiple small, low-cost missions to work together to address larger outstanding Mars questions.

A key principle of the Braided River is *openness*—the low-cost program as envisioned by the MCE-SAG offers the community regular opportunities to develop missions aligned with the overall 'Dynamic Mars' theme but is not overly prescriptive as to which track should be followed or which approach taken. This 'bottom up' mission development approach has been a core desire of the Mars community and is an essential element of the Braided River concept. Additionally, the Braided River is designed to have *parallelism*—sequential missions may pursue different science tracks, and not require waiting for the first mission to conclude before flying the second. In this way, it allows progress on multiple fronts—all contributing towards the same overall programmatic theme. As such, the Braided River is *flexible*, with 'off-ramps' that allow the program to transition between the five tracks as the state of the science evolves. Lastly, the Braided River *prioritizes* the most important science, and starts with those missions that are 'ready to go,' while enabling technology development for future high-priority missions. In a general sense, the SAG has found that orbital missions are likely to be most feasible in the short term, as most of the necessary technology is available for their implementation in a low-cost framework. Low-cost landed missions will require more time to develop, with hard landers likely being ready in a shorter timeframe than soft landers. While this general framework is the sense of the SAG, it is not seen as required—missions of any type can, and should, be competed when they are ready, regardless of architecture.

As the program is designed to be open, the MCE-SAG did not attempt to prescribe individual missions to fly to address the priority investigations; however, it did evaluate whether there were instrument/mission concepts that could accomplish some, or all, of each investigation. A broad selection of the orbital instrument/mission concepts that have the potential to fly early in the Dynamic Mars program were run through existing, simple parametric models to evaluate whether they could viably operate in a low-cost program. Most were able to fit within a ~$300M cost cap (Phase A-D), and many more within a Discovery cost cap (~$500M),

but some appeared to exceed even this value using current costing models and with current technology. The SAG explored the largest cost levers and what would be necessary to reduce the cost of some of these orbital missions. Key among these would be the opportunity to offload some spacecraft components from individual missions (e.g., telecom, large propulsion) to other assets at, or going to, Mars (e.g., a telecom orbiter or small satellite delivery system). Additionally, advances in autonomy and miniaturization would help reduce payload and operations costs. Technology development in these areas is a core part of the proposed lower cost program and should be specifically supported along with mission development. Lastly, greater risk tolerance can significantly reduce mission cost in some areas, by reducing redundancy and expected mission lifetime.

While not included in the aforementioned mission costs, payload delivery is another significant driver behind making this a successful program. Launch, cruise, and propulsion systems can influence the ability to fly low-cost missions, and the cadence on which they can occur. When these challenges are overcome, a lower-cost mission program as envisioned by the MCE-SAG can be highly enabling to the MEP, offering the opportunity to augment or replace existing infrastructure, provide landing site evaluation, make in situ resource utilization (ISRU) assessments, and perform weather monitoring, all of which will be critical for both future robotic and human exploration.

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1. Introduction

In the Spring of 2022, the Mars Exploration Program Analysis Group (MEPAG) chartered a science analysis group (SAG) to explore options for conducting new scientific exploration at Mars in the time of Mars Sample Return (MSR). The MSR program is a large endeavor designed to return carefully curated samples from the martian surface to Earth. The Mars 2020 rover *Perseverance* has begun the process[2] of collecting these samples and depositing them on the martian surface for eventual delivery to the MSR Sample Return Lander (SRL), which is anticipated to launch from the martian surface and return the samples to Earth as early as 2033[3]. Given the enormity of this program (both logistically and fiscally), it was deemed prudent by MEPAG to explore options for smaller-scale, and lower-cost, missions during the next decade (2023-2032)—missions that would offer continued new opportunities for Mars exploration by the community, while not diverting significant resources from the MSR program or from elsewhere in NASA's Planetary Science Division (PSD). This approach was echoed by the National Academies Planetary Science and Astrobiology Decadal Survey, *Origins, Worlds and Life* (*OWL*), which provided similar guidance for the Mars Exploration Program (MEP) to develop an exploration architecture that included opportunities for lower-cost payloads.

With this background, the Mars Concurrent Exploration Science Analysis Group (MCE-SAG) was chartered[4] in April 2022 with the following statement of task:

"The MEPAG Steering Committee forms the MCE-SAG to identify and prioritize scientific objectives and/or investigations that could be executed within the next ten years, in parallel with the MSR effort and in conjunction with *OWL* guidance for the Mars Exploration Program (MEP). The MCE-SAG shall:

- Identify high-priority science objectives that could be achieved in parallel with MSR to address fundamental planetary science questions traceable to the MEPAG goals document and the *OWL*, as well as recent SAG report findings and recommendations.
- Assay these objectives to identify constituent parts that are executable as standalone investigations that contribute to a broader program of Mars science.
- Determine how such investigations might be addressed within a low-cost mission program (Discovery budget class and smaller missions) within the next decade.
- Determine what technology development and Mars infrastructure will be needed to support these low-cost Mars missions."

Results from the MCE-SAG are designed to be incorporated into the strategic planning efforts of the MEP. A presentation of the results was given to both the community and the MEPAG Steering Committee at a public MEPAG meeting in November 2022, along with a separate presentation to the MEP and its future planning sub-group. This final report will be released approximately concurrently with the MEP Future Plan.

[2] The first cache has been collected and deposited as of January 2023.
[3] As of publication, the MSR program remains unconfirmed, and so all description and timeline of future Mars Sample Return activities should be considered notional.
[4] The full MCE-SAG charter may be found in Appendix 1.

2. Preliminary Activities

Plans to form the MCE-SAG membership were initiated by the MEPAG Steering Committee in April 2022. The MEPAG Steering Committee selected Dr. Michael Mischna (JPL/Mars Exploration Program Office) and Dr. Briony Horgan (Purdue University/MEPAG Steering Committee) to lead the activity. The selection of these two chairs ensured that the SAG leadership would be fully cognizant of the intent of the activity and ensure that the needs of the respective interested parties (the Mars Exploration Program Office and MEPAG) would be met. Following this selection, MEPAG issued an open call[5] to the community seeking participation in the SAG. Announcements were widely distributed across the major planetary newsletters and social media to attract interested members of the community. By the end of the designated application period, a total of 40 applications were received by the Steering Committee.

During this time, and before applications were received or reviewed, the Steering Committee met to establish an objective rubric by which applicants would be evaluated on such criteria as area of expertise, ability to support the notional timeline of the SAG, and expressed interest in the purpose of the SAG activity. Additionally, other secondary metrics were obtained (including career level, location, program, mission and/or costing experience) to ensure that SAG membership covered all meaningful axes of diversity within the Mars community. With agreement on the structure of the rubric, the Steering Committee undertook a process of reviewing the applications in June 2022.

After review of all applications, each Steering Committee member was asked to score each application according to the primary criteria established in the rubric, as well as the secondary metrics identified above, and provide their scoring to an independent arbiter not involved in the evaluation process. Of the 40 applications, a total of 21 were selected for participation in the SAG after review of the overall scores by the Steering Committee.[6]

The MCE-SAG weekly meetings were scheduled at two separate times/days on alternating weeks, with the express understanding that attendance was desired at least every other week for all SAG members. Many members were able to participate weekly, ensuring a healthy quorum for all decisions. The format for all meetings was WebEx—no in-person meetings were held. Meetings lasted for two hours, and were recorded and made available to SAG members, along with transcripts of the WebEx chat and all presentation slides, immediately following the meeting. To ensure steady engagement of the members, 'homework' was assigned after each meeting to provide content to act upon in future meetings.[7]

The overall structure of the MCE-SAG process followed the layout of the chartered Statement of Task and proceeded mostly linearly in addressing the four assigned tasks. The first effort of the SAG was to identify high-priority science objectives that were traceable to the MEPAG Goals document, the *Origins, Worlds and Life* Decadal Survey, and other community reports. Once these top-level science objectives were established, the members developed sample investigations that could be conducted to address these objectives. These investigations (purposefully written so as to be agnostic to implementation) were then converted into mission

[5] Text of the community announcement may be found in Appendix 2.
[6] A list of the MCE-SAG members and their affiliations may be found in Appendix 3.
[7] The schedule and timeline of the MCE-SAG activities may be found in Appendix 4.

concepts, including instrumentation with cost and risk assessment where possible. Lastly, the SAG identified technology and infrastructure necessary for implementation of these mission concepts, both individually, and more broadly, as part of a low-cost mission program.

Though the MCE-SAG's charter gave it freedom to self-identify the highest priority science objectives of the community, it was nevertheless constrained by guidance from the Decadal Survey, which explicitly laid out several findings and priorities for MEP that the MCE-SAG integrated into deliberations. These include conducting activities leading towards human exploration of Mars (so-called 'precursor' science, cf. Goal IV of the MEPAG Goals document), and an emphasis on objectives involving the search for extant life and assessment of modern habitability. The Decadal Survey identified a mid-class (i.e., New Frontiers-class) 'Mars Life Explorer' (MLE) mission to Mars for the purpose of searching for extant life as the next larger-class Mars mission for the coming decade. While MLE is outside of the purview of this SAG, it represents a major element of the future MEP that could run in parallel with a low-cost program. Given this framework, the MCE-SAG undertook its work to "*identify and prioritize scientific objectives and/or investigations that could be executed within the next ten years, in parallel with the MSR.*"

In the following sections, this report lays out the inputs and process used by the MCE-SAG in its deliberations (Sections 3-4), followed by discussion of the objectives for a low-cost mission program and individual investigations to address the objectives (Section 5). The report then provides the MCE-SAG's recommended path forward for a low-cost mission program (Section 6), concluding with a discussion of technical and programmatic considerations that would better enable the program as envisioned by the MCE-SAG (Section 7). Results of the MCE-SAG costing exercise for sample mission concepts are given in Section 8, followed by a summary of the MCE-SAG findings in Section 9.

3. SAG Inputs

3.1 External Speakers

To augment the broad expertise of the group, the MCE-SAG solicited additional input from external experts in science, programmatics, mission design and technology to augment its work and better frame aspects of its underlying charter. Over the course of the three-month period over which the SAG conducted its work, it received four sets of external contributions, which are highlighted, in brief, below.

3.1.1 Phil Christensen—Decadal Survey Perspective

As co-chair of the Steering Committee of the Decadal Survey, Phil Christensen provided a high-level overview of the Decadal Survey deliberations as they pertained to Mars and offered perspective as to how the Decadal Survey Steering Committee envisioned low-cost missions fitting into the Mars Exploration Program. Key points of his presentation included emphasizing the need for the MEP to 'develop and execute a comprehensive architecture of missions' (of all classes). Central among these is a strategic, medium-class mission focusing on the search for life. Both modern ice and the search for life were seen as some of the most compelling science questions at Mars. Additionally, it was noted that the potential high cadence of low-cost missions could allow the MEP to respond to discoveries in a reasonable time. Drawing on the experience of the failure of the Mars Observer mission, the rise of 'faster, better, cheaper' in the 1990s was a way to increase the cadence of exploration with missions of more limited scope than Mars Observer. The current study can be seen as paralleling that approach by, again, limiting mission scope and increasing frequency during this cost-constrained period of Mars Sample Return, but now remaining fully aware of, and embracing, the higher-risk nature of small missions.

3.1.2 Eric Ianson and Tiffany Morgan—MEP Perspective

Eric Ianson and Tiffany Morgan, Director, and Deputy Director of the Mars Exploration Program, provided contextual information to the MCE-SAG about the role of the study in the broader MEP strategic planning process. While it was anticipated that this report would feed into the MEP strategic plan as an element of the science program, the deliberations of the MCE-SAG are also relevant to the areas of infrastructure and of partnering with international and commercial entities. Of note, it was stated by MEP leadership that, "the best ideas come from competition, which also keeps the community engaged". This point plays a significant role in the content of this report, where the MCE-SAG has sought to ensure open competition and community engagement through a regular cadence of low-cost missions. We were encouraged to explore links to other agency priorities, such as Humans to Mars, in our deliberations. It will be seen that the MCE-SAG has addressed this inter-Directorate priority in its work. Lastly, we were asked to develop an "inspirational" program—one that is exciting, fosters inclusivity, and keeps Mars at the forefront of planetary exploration.

3.1.3 Nathan Barba—Mission Design Perspective

Nathan Barba is a systems engineer supporting the MEP in advanced design engineering, investigating, and studying how to conduct low-cost missions at Mars. His presentation to the

MCE-SAG was designed to offer guidelines that would allow the team, itself, to conduct 'sniff tests' of investigations as they were first discussed, including those flying on orbiters, hard and soft landers, and other mobility systems. His insight into costing of such missions provided the SAG with a perspective on the biggest lever arms that drive mission cost, especially important for cost-constrained missions. The discussion spanned multiple axes that drive mission cost, including the method of getting to Mars (e.g., 'piggybacking', Earth rideshare + propulsion, or a dedicated launch), the final desired orbit, mission class, means of propulsion, and landing system. While acknowledging the challenges inherent in reducing cost, the conversation struck an optimistic tone, with numerous avenues by which missions might fit within the SAG-defined cost cap ($100-500M). Apart from the issues identified above, payload size must be a strong consideration, with plausible orbital payloads being in the range of 20-40 kg and potential landed payloads around 5-15 kg. Although these values are no more than initial estimates, it did provide the SAG with rough bounds for potential payloads which might be flown in this mission class. A more detailed exploration of mission cost followed and results from that work are discussed in Section 8.

3.1.4 Chad Edwards and Larry Matthies—Technology Perspective

Representing the Mars Exploration Program Advanced Studies office, Chad Edwards and Larry Matthies discussed some of the technological challenges facing the development of smaller and lower cost spacecraft, including size and mass constraints, and instrument deployment, particularly on surface landers. While the Advanced Studies office does not generally focus on instrument technologies but, rather, spacecraft technologies, identifying such broader areas of ongoing development was a helpful exercise to see which of the notional mission concepts developed by the SAG appeared viable in the near term, and which required additional time to reach fruition. Based on a list of notional investigations compiled by the MCE-SAG later in its deliberations, this discussion provided an opportunity for a second 'sniff' test of deliberated mission concepts. The discussion also brought the MCE-SAG into closer alignment with the Low-Cost Science Mission Concepts for Mars Exploration workshop, which preceded the MCE-SAG activities, and addressed a similar theme. While the content of the workshop was previously available to the MCE-SAG, this discussion put those concepts under the lens of technology readiness, and identified more clearly how certain missions might be prioritized in terms of timing and readiness.

3.2 Framework for Identifying the High-Priority Science Objectives

3.2.1 Current MEP

Although the MCE-SAG study was conducted after the release of the *Origins, Worlds, and Life* Decadal Survey, it was sufficiently close to the transition from the *Visions and Voyages* (*V&V*) Decadal Survey that aspects of that prior study were folded into the group deliberations. Indeed, absent a new MEP strategy (for which this work will be a contributing element), there is value in retaining and transitioning some elements of the prior strategy into the current work.

Current MEP strategy has responded to the *V&V* report by directly addressing the three high-priority science goals for the exploration of Mars as stated in *V&V*:

- Determine if life ever arose on Mars.

- Understand the processes and history of climate.
- Determine the evolution of the surface and interior.

The first of these goals is a natural extension of the prior MEP strategy to “Explore Habitability”. The *Curiosity* rover was the predominant mission of the MEP during this time frame that addressed this goal—were conditions on Mars conducive to the establishment and sustenance of life on Mars? Were the conditions necessary to provide a habitable environment present on Mars in the past? Among these, the presence of water, organic compounds, and chemical gradients as sources of energy are key. The *Curiosity* rover conclusively established that its Gale crater landing site contained all these elements.

Likewise, the arrival of *Perseverance* in Jezero crater confirmed the presence of these important components, indicating that habitable environments are widespread across Mars. The desire to determine whether life ever arose on Mars evolved into a strategy to ‘Seek Signs of Life’ on Mars; seeking out potential ancient biosignatures is the primary task of the Mars 2020 mission, both through in situ investigations and sample collection for Mars Sample Return.

In parallel, NASA has continued addressing the other *V&V* science goals at a steady pace. Results from other recent landed and orbital missions, including *Phoenix*, MAVEN, and InSight[8], demonstrate the importance of climate, surface, and interior science to Mars exploration. Pursuit of these investigations, along with those of extant life described above, remains an emphasis in the new Decadal Survey, which is discussed in the next section.

3.2.2 Decadal Survey Recommendations

The National Academies of Sciences, Engineering, and Medicine (NASEM) report titled “*Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023-2032*” (*OWL*) outlines the highest priority scientific activities to guide the coming decade of planetary exploration. The Decadal Survey report includes a description of the most compelling science questions, goals, and challenges to motivate the next decade of planetary science and astrobiology exploration and research strategies. Within this framework, Mars plays a key role in addressing multiple scientific topical areas such as planetary formation and evolution, atmospheric processes, ice and climate history, and habitability and the search for life, as described below. The *OWL* report also demonstrates that Mars is a key component of comparative planetology studies, with investigations of martian processes often referenced as a way to understand phenomena at play across the broader Solar System and beyond, given the unique aspects of planetary evolution that are recorded on its surface.

Unlike prior Decadal Surveys, the *OWL* report does not focus on specific Solar System bodies but, rather, on high-priority and crosscutting science questions that are potentially applicable to multiple destinations, including Mars. In this section, we capture those elements of *OWL* that are relevant to Mars (Table 1). It will be seen in later sections how these elements feed into the Mars scientific objectives identified by the MCE-SAG.

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[8] while nominally a part of the NASA Discovery program, it is nevertheless included here in the discussion of Mars Exploration Program science.

Table 1: *Mars-relevant questions prioritized by the OWL report that informed the MCE-SAG*

OWL Question	Sub-question
Q3: Origin of Earth and Inner System Bodies	Q3.4: What processes yielded Mars, Venus, and Mercury and their varied initial states? Q3.5: How and when did the terrestrial planets and Moon differentiate? Q3.6: What established the primordial inventories of volatile elements and compounds in the inner Solar System?
Q4: Impacts and Dynamics	Q4.2: How did impact bombardment vary with time and location in the Solar System? Q4.3: How did collisions affect the geological, geophysical, and geochemical evolution and properties of planetary bodies? Q4.4: How do the physics and mechanics of impacts produce disruption of and cratering on planetary bodies?
Q5: Solid body interiors and surfaces	Q5.1: How diverse are the compositions and internal structures within and among solid bodies? Q5.2: How have the interiors of solid bodies evolved? Q5.3: How have surface/near-surface characteristics and compositions of solid bodies been modified by, and recorded, interior processes? Q5.4: How have surface characteristics and compositions of solid bodies been modified by, and recorded, atmospheric processes? Q5.5: How have surface characteristics and compositions of solid bodies been modified by, and recorded, external processes? Q5.6: What drives active processes occurring in the interiors and on the surfaces of solid bodies?
Q6: Solid Body Atmospheres, Exospheres, Magnetospheres, and Climate Evolution	Q6.1: How do solid-body atmospheres form and what was their state during and shortly after accretion? Q6.2: What processes govern the evolution of planetary atmospheres and climates over geologic timescales? Q6.3 What processes drive the dynamics and energetics of atmospheres on solid bodies? Q6.4 How do planetary surfaces and interiors influence and interact with their host atmospheres? Q6.5 What processes govern atmospheric loss to space? Q6.6 What chemical and microphysical processes govern the clouds, hazes, chemistry, and trace gas composition of solid body atmospheres?
Q10: Dynamic Habitability	Q10.2: Where are or were the Solar System's past or present habitable environments? Q10.3: What controls the amount of available water on a body over time? Q10.4: Where and how are organic building blocks of life synthesized in the Solar System? Q10.5: What is the availability of nutrients and other inorganic ingredients to support life? Q10.6: What controls the energy available for life? Q10.7: What controls the continuity or sustainability of habitability?
Q11: Search for Life Elsewhere	Q11.1: What is the extent and history of organic chemical evolution, potentially leading toward life, in habitable environments throughout the Solar System? Q11.2: What is the biosignature potential in habitable environments beyond Earth? Q11.3: Is or was there life elsewhere in the Solar System? Q11.4: What is the nature of life elsewhere, if it exists?

Studies of Mars play a key role in advancing our understanding of planetary formation and evolution, as highlighted within *OWL* Priority Science Question 3 ('Origin of Earth and Inner System Bodies'). After its early formation, Mars was subjected to multiple processes that altered

the planet; these processes are addressed in *OWL* Question 4 ('Impacts and Dynamics'). Solid body interiors and surfaces are addressed by *OWL* Question 5, where studies of Mars contribute significantly to nearly every sub-question. Studies of the earliest period of martian history are directly called out in sub-questions regarding the formation and early evolution of planetary atmospheres within *OWL* Question 6 ('Solid Body Atmospheres, Exospheres, Magnetospheres, and Climate Evolution').

Ice on Mars serves as a record of martian climate history and is a key target for habitability and life detection investigations. *OWL* Questions 5 and 6 includes several sub-questions that tie directly into recent climate evolution, including those that address present-day ice processes. Studying such processes is necessary to understand the present-day coupled dust, water, and CO_2 cycles on Mars, but is also crucial for understanding how these processes operated in the past and formed the ice record of past climate we see today in polar and mid-latitude deposits.

The dynamic nature of Mars makes it a uniquely well-suited and accessible destination for directly observing and understanding both processes with connections to terrestrial phenomena and processes that occur well outside of terrestrial conditions. As such, Mars is repeatedly called out by Questions 5 and 6 of the *OWL* report as a subject of investigation of modern active processes. Addressing these questions at Mars provides an important tie point for broader studies of comparative planetology, specifically related to the atmosphere and surface-atmosphere interactions. The majority of these questions reference martian water and dust activity.

Understanding habitability and searching for life elsewhere in the Solar System is a key objective outlined in the *OWL* report, which spans multiple *OWL* priority science questions, including Q10 ('Dynamic Habitability') and Q11 ('Search for Life Elsewhere'), and capitalizes on research pertaining to Q9 ('Insights from Terrestrial Life'). Given the identified past habitability and potential present habitability of Mars, the Red Planet serves as a key target destination to address multiple specific priority science questions from *OWL*.

Given the importance of understanding Mars habitability, the Decadal Survey has prioritized a life detection mission for Mars as a strategic mission for MEP, using the MLE mission concept as an example that addresses this need. The MLE mission would search for signatures of life and seek to understand habitability of near surface ice on Mars by *1*. searching for modern biosignatures, *2*. characterizing subsurface thermophysical properties and the habitability of ice/ice-cemented regolith, and *3*. quantifying the near-surface water vapor flux associated with ice and mineralogy over one martian year. The MLE mission would thus address three priority science questions from the *OWL* report: Questions 6, 10, and 11.

3.2.3 Linkages to Other Program Documents

The MCE-SAG activity was designed to be complementary to other recent activities within MEP and the Mars community. In addition to the Decadal Survey, the MCE-SAG was viewed as an opportunity to synthesize several MEP studies and activities conducted in recent years and provide specific pathways to implement missions recommended by these studies in the next decade. It is closely related to the Mars Architecture Strategy Working Group (MASWG), from which it draws inspiration, but the MCE-SAG has an expressly different purpose. Whereas MASWG was designed to visualize an entire Mars program architecture for the future, the MCE-SAG focuses on low-cost missions (an element of the MASWG report).

The MASWG report [MASWG, 2020] was initiated in response to the NASEM mid-Decadal review, which expressed a need for concrete plans for MEP during, and after, the era of MSR. MASWG reinforced the need for a continued, dedicated MEP to support critical and unique science at Mars and prepare for human exploration of Mars. The report identified open science questions for Mars exploration and recommend that MEP should address these science questions through one or more series of related “arcs” of missions. While MASWG was not prescriptive in terms of the specific missions or science questions that should be addressed first, the report provided example mission arcs with themes that could address a broad range of questions. The mission arc themes included: *1*. Diverse ancient environments and habitability; *2*. Subsurface structure, composition, and possible life; *3*. Geologically recent climate change; *4*. Atmospheric processes and climate variability. The key exploration themes identified here by the MCE-SAG were informed by and, in part, evolved from, those proposed in the MASWG report. While MASWG provided example mission arcs addressing high level science questions that could be implemented by a full range of mission classes, it did not provide a detailed mission architecture that could be conducted in the short term, and with low-cost missions. In this way, this MCE-SAG report identifies a path forward that can be conducted in parallel with the Mars Sample Return program, i.e., over the next decade, while the MASWG report identifies a more ambitious program that can be conducted once the cost and effort of MSR is in the rear-view mirror.

Separately, the Keck Institute for Space Studies (KISS) conducted a study program “Revolutionizing Access to the Mars Surface” prior to the activities of the MCE-SAG. This KISS program’s final report [KISS, 2022] proposed a ‘Frequent, Affordable, Bold’ (FAB) programmatic approach to low-cost Mars exploration that endeavors to integrate NASA and non-NASA stakeholders in future efforts to reach the martian surface. The FAB strategy emphasizes the importance of mission arcs because they would enable the “predictable high cadence of missions” that is crucial for generating economy of scale and cost savings.” The higher science return per dollar expected for more frequent, lower-cost missions with shorter lifetimes would compensate for the anticipated higher risk. Near-term steps suggested by the KISS report to implement the FAB-style program included developing a “science roadmap” between MEPAG Science Goals and mission types. This MCE-SAG report addresses this need by identifying and prioritizing scientific objectives that could be addressed within a low-cost mission architecture in the coming decade.

The Low-Cost Science Mission Concepts for Mars Exploration workshop convened in spring 2022 to discuss the feasibility, from both scientific and technical perspectives, of Mars missions in the $100–300M price range (or between SIMPLEx—The Small Innovative Missions for Planetary Exploration program—and Discovery). The workshop was, in part, motivated by findings from the MASWG report. There was clear consensus from the workshop attendees that compelling science can be done at Mars within a $300M cost cap. Key challenges to conducting low-cost Mars missions include getting to Mars and, for some concepts, delivering payload to the martian surface. Getting to Mars as a low-cost mission requires identification of a suitable launch vehicle, securing communication from Mars (i.e., a need for a telecommunications infrastructure), and overcoming the traditional programmatic posture of low risk tolerance, among other challenges. Innovative approaches for landing on Mars may enable low-cost access to the surface, but, again, an acceptance of higher risk is necessary. The current state of technological readiness for Mars exploration as summarized by the Low-Cost Mars Exploration

workshop was considered when assessing the feasibility of possible mission architectures outlined in this report.

The MCE-SAG activities also considered the following community studies:

- *The final report of the Ice and Climate Evolution Science Analysis Group (ICE-SAG)* [MEPAG, 2019]. This was particularly valuable in assessing the range of investigations to address the Recent Climate Evolution and Dynamic Modern Environments objectives (Sections 5.3-5.4).
- *The activities of the International Mars Ice Mapper (I-MIM) Measurement Definition Team (MDT)*. While the final report of the MDT was released one week prior to the conclusion of the MCE-SAG activities, the SAG was graciously provided a pre-release draft of the report for its deliberations. This report, too, supported the Recent Climate Evolution objective (Section 5.3).
- *The Next Mars Orbiter Science Analysis Group (NEX-SAG) report* [MEPAG NEX-SAG Report, 2015]. Elements of this study identified high-priority science investigations as viewed through the lens of the *V&V* Decadal report. The NEX-SAG report fed into the MCE-SAG objectives of Early Environmental Change, Recent Climate Evolution and Dynamic Modern Environments (Sections 5.2-5.4).
- *Presentations given at the May 2022 MEPAG meeting in Denver, CO*. In preparation for the MCE-SAG activities, MEPAG solicited community input on the topic of 'Mission Concepts for the Next Decade'. Output from the lightning talks and breakout sessions conducted at the meeting were collected and made available to MCE-SAG and provided input for all five science objectives.
- *ESA's Terrae Novae 30+ report*. ESA's strategy roadmap, *Terrae Novae 2030+*, has, as one of its objectives, to prepare for the first European to Mars by 2040. Elements of the notional Mars strategy include elements having strong overlap with the MCE-SAG's charter, including development of small and fast-track platforms for conducting "a regular series of missions offering increased diversity in missions within the programme and opportunities for complementary science to the larger strategic missions…" [ESA, 2022]. Areas of synergy with the Terrae Novae plan were highlighted in the MCE-SAG activities.

4. SAG Processes

4.1 Refining High-Level Science Objectives

The first of the four chartered tasks required the MCE-SAG to "identify high-priority science objectives that could be achieved in parallel with MSR to address fundamental planetary science questions traceable to the MEPAG goals document and the *OWL*, as well as recent SAG report findings and recommendations." To achieve this task, and to kick off the overall MCE-SAG effort, the team developed a list of individual science objectives seen as high priority by a plurality of members. Demonstration of the value of individual objectives was made by providing clear linkage to *OWL* and/or the MEPAG goals document (or other community reports), as well as programmatic tie-in to other elements of future Mars exploration, including MSR, the MLE mission (as recommended in *OWL*) and a prospective human exploration program.

From this compiled list, the MCE-SAG identified common elements among multiple proposed objectives leading, ultimately, to refinement into five core objectives: Geophysics, Ancient Environments, Ice Processes, Current Processes, and Modern Habitats. As the MCE-SAG work continued, it became clear that there was an underlying, cross-cutting theme in these objectives of understanding drivers of change on Mars as an active planet. Ultimately, the MCE-SAG established an overarching programmatic theme of 'Dynamic Mars' and chose to reword its five proposed objectives for clarity, and to align them more closely with this theme (Figure 1). The 'final five' science objectives therefore became:

- **Planetary Evolution (PE):** Characterize the geodynamic, petrologic, thermal, and tectonic evolution of the crust and interior of Mars from the Pre-Noachian through the present day.
- **Early Environmental Change (EE):** Understand the processes that drove habitability and climate change on early Mars as recorded in the ancient stratigraphic record.
- **Recent Climate Evolution (RC):** Understand modern volatile transport and the drivers of recent climate change using global ice records and atmospheric reservoirs.
- **Dynamic Modern Environments (DM):** Understand processes responsible for the modern surface and atmospheric environments by characterizing meteorology, atmospheric fluxes, and other dynamic processes on Mars.
- **Modern Habitability (MH):** Search for currently or recently habitable environments and present-day life on Mars.

As seen in Figure 1, there was generally a one-to-one correspondence between the original objectives and these refined forms, with the exception of 'Current Processes' which was bifurcated into both 'Recent Climate Evolution' (processes occurring geologically recently, but on qualitatively 'long' timescales) and 'Dynamic Modern Environments' (processes occurring presently, and on much shorter timescales). Below, we discuss the process by which individual science investigations were established within each objective and, in Section 5, we use these five objectives and subordinate investigations to establish a series of science 'tracks' for a notional low-cost program.

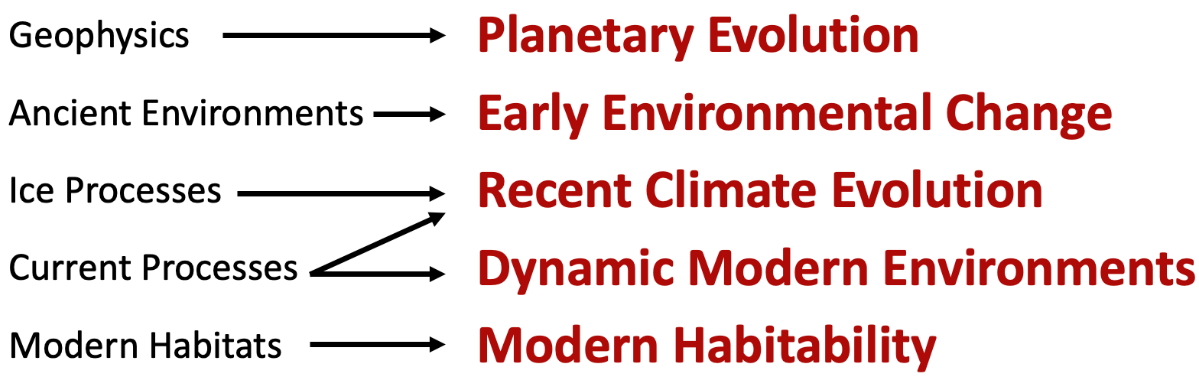

***Figure 1**: Mapping of original MCE-SAG objectives (left) to the final form of five exploratory 'tracks' for the notional low-cost program.*

4.2 Developing Science Investigations and Science Priority

With the establishment of the original science objectives, the MCE-SAG members were asked to identify science questions from *OWL* and the MEPAG Goals document that were relevant to each objective. This linkage to *OWL*, particularly, was seen as an essential element of the process, linking the MCE-SAG findings directly to the foundational Decadal Survey report. Synthesizing overlaps between questions began to reduce a lengthy list into a more manageable collection of science investigations that covered the Mars-relevant Priority Science Question topics in *OWL*, outlined above in Section 3.2.2 and shown in Table 1.

For each of the five science objectives, between 4-8 investigations were specifically called out as most strongly addressing the underlying objective, tying into other NASA priorities (e.g., MSR, Humans to Mars), and having the potential to be addressed in a low-cost program. Because of the varied expertise among the SAG membership, participants tended to 'self-select' areas of interest to which they would contribute. Each of these five 'sub-groups' then continued refinement of the investigations and their description, as well as prioritization of the individual investigations.

Initially, the SAG attempted to assign a prioritization 'score' to each of the investigations across all five objectives. Members were asked to rank their view of the relative priority of one investigation versus another, but the approach revealed a clear familiarity bias (where members tended to rank as more important those investigations that aligned with their interest or understanding). This became clear in a breakdown of the initial prioritization scoring. After further discussion among the group, it was decided that another attempt at prioritization would be made, but this time within each individual objective.

To conduct this prioritization, the individual investigations were compared to the priority assigned to related investigations in the MEPAG goals document, as the latter document reflects the overall community consensus on science priority. However, as the MCE-SAG investigations did not directly map to individual MEPAG investigations, there was flexibility in the ranking activity. Within each objective, subordinate investigations were put into one of four categories: High, High/Medium, Medium, and Low. Full dynamic range across all four categories was not a requirement for the objectives and, in some objectives, multiple investigations received a 'High' classification, and none received a 'Low' classification. It should also be noted that, as with the MEPAG goals prioritization, a 'low' priority does not imply that an investigation is not worthy of

pursuing, but that it is less likely to be a standalone motivation for mission development and selection.

With the investigations now roughly classified according to science prioritization, the SAG next addressed the question of feasibility of conducting each investigation under a low-cost program, and within the timeline bound by the Decadal Survey.

4.3 Assessing Feasibility

Establishing feasibility of individual investigations was a multi-step process that evolved as the SAG learned more about available technology, mission costs, and programmatic constraints (see Section 3). Additionally, it was observed that some investigations could be feasibly conducted in multiple parts, though perhaps not in a single mission. This is an important point that draws a distinction between 'investigation' and 'mission.' An investigation describes pursuit of answers to a scientific question, but is agnostic to the approach taken, whereas a mission is the specific implementation designed to conduct the investigation. The SAG determined investigation feasibility based on whether the investigation could be conducted by a reasonable number of parts (if multiple low-cost missions were necessary), and not whether it could be completed by one mission.

The team chose to consider feasibility in simple terms. Most investigations that could be addressed by an orbiter, with mature and low-to-moderate mass payloads, were deemed as having 'high feasibility.' Investigations that could be performed by a hard or rough lander, or by an orbiter with less mature or heavy payloads were of 'medium feasibility.' Investigations that required soft landing, direct subsurface access, or a complex payload, were of 'low feasibility'. This assessment focused on the feasibility of making the requisite observations to address the investigation with current technology and within a low-cost program and did not account for components such as spacecraft delivery to Mars, telecom relay or other required infrastructure. These will be discussed in Section 7. With a feasibility ranking assigned, a two-dimensional matrix of science priority vs. feasibility was established (Table 2).

Missions of both higher science priority and higher feasibility rank are found in the upper left of the matrix, shaded in green, and listed by identifier corresponding to their overarching objective and an index number (non-prioritized). Descriptions and details of these, and all other, investigations may be found in Appendix 5. Six investigations (PE1, PE2, EE1, RC1, DM2, DM4) were seen as the most viable to pursue in the first mission or missions under this low-cost program (dark green). Six more investigations were of high science priority but appeared to require more development before readiness (light green).

This assessment made it clear that all five objectives have investigations deemed to be of significant science value that are ready (or nearly ready) for implementation. The question of how to choose among, or integrate, these investigations to develop mission concepts drove much of the second half of the MCE-SAG activity and led to some of the more prominent elements of the low-cost program discussed below.

Table 2*: Matrix of science priority vs feasibility for the 28 investigations considered by the SAG. Nomenclature identifies the specific objective and investigation index number (the latter not suggesting prioritization). PE = Planetary Evolution, EE = Early Environmental Change, RC = Recent Climate Change, DM = Dynamic Modern Environments, MH = Modern Habitability.*

		Science Priority			
		High	High/Medium	Medium	Low
Feasibility	High	**PE1, EE1, DM2**		**PE2, RC1, DM4**	**RC6**
	Medium	**RC2, MH1, DM1**	**PE3, EE3, DM8**	**RC4, MH3, MH4, DM5**	**DM6, DM7**
	Low	**EE2, RC3, MH2**	**PE4, DM3**	**PE5, RC5**	**PE6, EE4**

4.4 Formulation of the 'Braided River' Architecture Concept

Establishing the structure of a low-cost program from the internal discussion about science priority and feasibility arose organically once the theme of 'Dynamic Mars' was established, and the individual investigations were triaged for science priority and mission feasibility. The five individual objectives that arose from the initial discussions were reframed as investigation 'tracks,' within which the individual investigations would reside (Figure 1). As noted in Section 4.3, individual investigations might very well require multiple missions within a single track to complete, and some missions might bridge multiple tracks. This potential architecture mirrors how some of the biggest advances in Mars science have come about: from the integration and synthesis of multiple datasets, from multiple instruments, potentially on multiple spacecraft. Taking a similar approach with low-cost missions also allows some larger problems to be broken apart and addressed in smaller 'chunks,' perhaps by multiple missions either in sequence, or conducted in parallel.

Further, there are clear relationships between the individual tracks, beyond just the overarching theme of 'Dynamic Mars.' For example, understanding the structure and formation of mid-latitude ice on Mars (Recent Climate Evolution) requires studying signs of recent climate evolution but also requires knowledge of present-day atmospheric processes (Dynamic Modern Environments), and even the physics and formation of liquid water in near-surface environments (Modern Habitability). Aspects of such an investigation may cross multiple tracks, or objectives. Thus, the notion of a 'Braided River' was used to describe the approach to establishing a functional, and viable, low-cost Mars program.

> **The Braided River:** An interconnected network of low-cost missions working together to address major outstanding Mars questions.

As the name suggests, our Braided River consists of an interconnected approach to Mars exploration. In a braided river, water from one 'channel' (track) mixes easily with water sourced from other channels (Figure 2). Furthermore, water can enter from many places and end up within the broader flow, moving toward the same destination. With the tracks serving as individual elements of the braid, along with example mission concepts often serving as crossovers in the braid, we show that many areas of investigation addressed with small missions could

contribute meaningfully across scientific disciplines and interests, enabling all investigation areas to advance forward under the umbrella of studying Dynamic Mars.

Figure 2: *The Rakaia river, in Canterbury, New Zealand, illustrating the concept of a 'Braided River' with interconnecting, merging, and splitting tracks. Image by Andrew Cooper (https://commons.wikimedia.org/wiki/User:Andrew_Cooper#/media/File:Rakaia_River_NZ_aerial_braided.jpg), licensed under CC BY 3.0 (https://creativecommons.org/licenses/by/3.0/)*

The notion of 'flow' in the braided river concept also reflects how a low-cost program can consist of successive phases of implementation, roughly corresponding to the feasibility metric discussed above. An initial phase might consist of comparatively simpler missions, such as orbiters, while subsequent phases may entail more complex orbiters or landers of various design. Advanced landed missions (e.g., involving drilling, or complex networked missions) might comprise yet a further phase.

A notional design of the Braided River may be seen in Figure 3, demonstrating the general structure of the concept. In this example, specific archetypal missions are shown in order to represent concepts that might address the higher priority science investigations of Figure 1. In Figure 3, each of the five tracks are represented as vertical bars—notionally independent of each other, but all falling under the umbrella of 'Dynamic Mars.' Within, and spanning, these bars are missions, and connecting these missions are branches of the 'river,' illustrating some scientific connection between missions. In many cases, these indicate how precursor mission science can

feed directly into design of a subsequent mission. In some cases, branches are meant to indicate how collaborative science with another mission may lead to discoveries warranting further investigation in a new direction. Missions in green represent those concepts that are simpler and deemed more feasible to implement initially. Blue and yellow boxes indicate progressively more complex mission ideas that appeared likely to operate only after further technological development. ***Figure 3 is meant to represent only a notional architecture to demonstrate the braided river concept and is not meant to advocate for any specific missions or concepts*—**the ultimate decision on what missions to fly to address the (purposefully implementation-agnostic) investigations would be left up to those proposing the missions, and NASA.

Further emphasizing the freedom that the Braided River concept provides are four key principles of this notional program architecture:

- *Openness*: Being overly prescriptive is detrimental—to make this program successful, NASA should offer the community opportunities to develop missions aligned with the overall theme (Dynamic Mars), using the tracks only as guiderails. Competition breeds the most compelling science, and regular, frequent competition keeps the whole community engaged.
- *Parallelism*: More than one possible track at the start can enable more frequent missions, allow progress on many fronts, and can foster cross-track synthesis. The structure of the Braided River does not require missions to be pursued only along one track at a time. Multiple investigations on different tracks can be pursued in an overlapping fashion, or even multiple investigations within a single track, as discovery and capability warrant. While it is beneficial for a mission to demonstrate scientific connection to prior activities, this is not strictly required, thus allowing the ability to respond to new or unexpected discoveries. To keep a rapid cadence and reduce latency, the low-cost program should therefore allow pursuit of multiple tracks in parallel.
- *Flexibility*: Tracks should offer 'off-ramps' that allow the program to transition between tracks as the science evolves. Rather than stay rigidly within a single track (which suffers from the slow cadence mentioned above), the program architecture should allow the flexibility to jump from one track to another as the science dictates. In cases where new science investigations arise from the blending of two tracks, the program should be flexible enough to enable redirection along a new path.
- *Priority*: A notional program should conduct high-priority science, starting with those missions that are "ready to go," while enabling tech development for other high-priority missions. This staged approach allows for missions to start immediately, while also pursuing the development necessary to enable new missions in the future.

This Braided River-type structure, with its science-focus flexibility, also positions the program well to easily incorporate new technology development in software, hardware, and delivery platforms. With numerous connections between science investigations and with there being high-priority advancements possible in multiple investigation areas, it would be useful to address more than one area within subsequent opportunities instead of advancing only one specific discipline or investigation area. Thus, an initial program selection can have a focus on "ready to go" concepts, with later calls easily adapted so as to be responsive to new science discoveries (leading to new high-priority science questions), technology advancements, or creativity within the planetary science community.

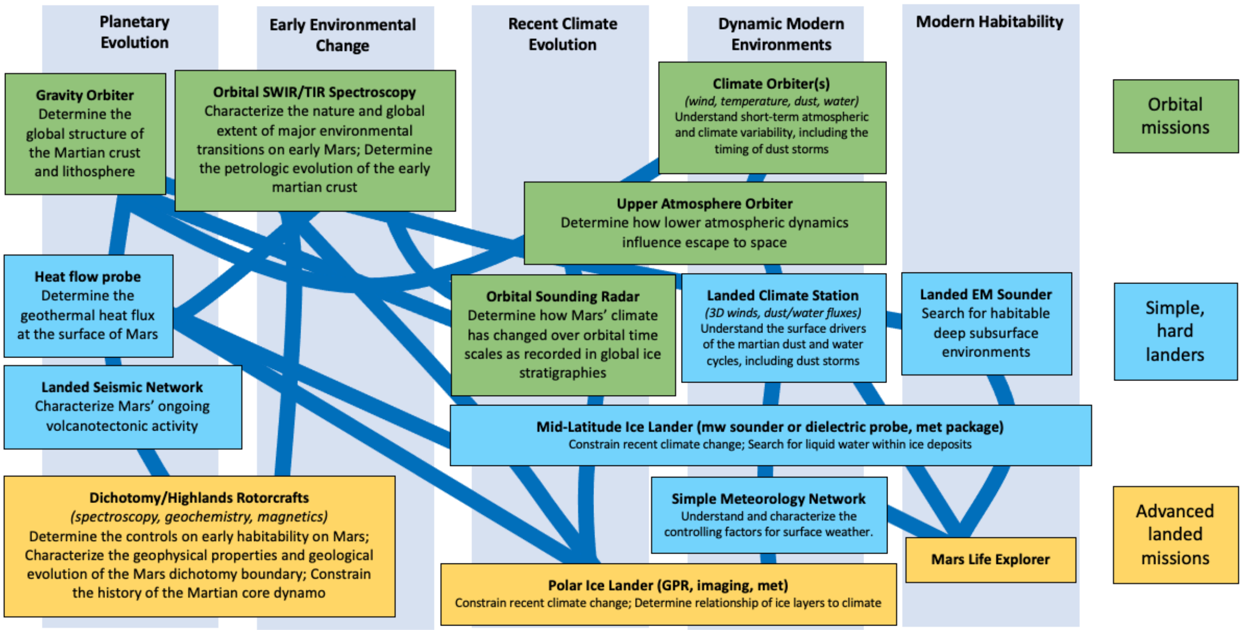

Figure 3*: A notional 'Braided River' concept incorporating the five high-level science tracks under the umbrella of 'Dynamic Mars'. Individual mission concepts are purely notional and are intended to demonstrate that high-priority investigations have at least one feasible path forward to their implementation. Other mission approaches, if vetted for cost and technology readiness, should be considered equally under the 'openness' and 'flexibility' principles of the Dynamic Mars mission architecture.*

Because of an emphasis on this program architecture being open to all ideas which fall within the guiderails of the five tracks and the theme of 'Dynamic Mars,' the MCE-SAG was hesitant to prescribe preferred missions to address the individual investigations. However, it was felt that a necessary exercise would be to determine that at least one implementation path was available to each investigation to fall under the constraints of a low-cost mission program. To accomplish this, the SAG membership scoured the available literature for instrumentation that would address the individual investigations and gathered information on instrument readiness (via its technology readiness level—TRL), size, weight, and power (SWaP) requirements, and other capabilities of the instrument to address the goals of the investigation. A list of instruments considered in the MCE-SAG study may be found in Appendix 6.

For the highest priority science investigations, information on possible instrumentation was fed into a JPL-institutional costing tool to provide a rough order of magnitude cost for a mission, as a means to check if the concept could fall within the ~$100-300M bounds of a low-cost program (or within the <$500M limit of a sub-Discovery program). Details on the biggest lever arms in the costing exercise are found in Section 8; however, in no case was any investigation in the list outright excluded due to excessive cost. All investigations were found to have at least one viable pathway forward in the Braided River. The path any one mission would take, both building upon prior investigations, and seeding possible directions for future investigations is, again, up to the competing proposer.

5. Objectives for a Low-Cost Mission Program

Summaries of the five science objectives presented above are provided here, with further detail provided in the appendices. For each objective, those investigations that rank higher in both science priority and feasibility metrics (i.e., those shaded in green in Table 2) are referred to as of 'high precedence,' and are called out separate from the other investigations. Appendix 5 lists all investigations along with their links to the *OWL* report and MEPAG Goals document, their science priorities, and anticipated feasibilities. For each investigation, sample instrument concepts are detailed in Appendix 6.

5.1 Objective: Planetary Evolution

The Planetary Evolution (PE) objective involves the characterization of the geodynamic, petrologic, thermal, and tectonic evolution of the planet over its entire history, from the pre-Noachian to the present day. Characterization of the evolution of Mars as a planet is scientifically compelling on its own, but also provides global context for other objectives, such as Early Environmental Change (Section 5.2) and Modern Habitability (Section 5.5). We have identified six compelling scientific investigations under this objective, including three investigations of higher precedence:

PE1: Determine the global structure of the martian crust and lithosphere, including the origin and nature of the hemispheric dichotomy.
PE2: Determine the composition and petrologic evolution of the early martian crust.
PE3: Characterize Mars' ongoing volcanic/tectonic activity.

These three investigations address outstanding questions in planetary evolution from geophysical, geochemical, and geological perspectives. One example of an outstanding question is the origin of the global crustal dichotomy, which represents a planetary-scale asymmetry in geology and topography and is Mars' largest feature. Whether the dichotomy also represents a global asymmetry in crustal density, crustal thickness, or both is uncertain but important in understanding its origin. The global dichotomy has both endogenic [Roberts, 2021] and exogenic [Citron, 2021] formation hypotheses, but its origin is uncertain and explicitly called out by the *OWL* Decadal Survey under strategic research question 5.2. Investigations PE1 and PE2 map to potential mission concepts with high feasibility. Determining the global structure of the crust and lithosphere would be greatly enabled by an orbital mission dedicated to collecting gravity data, while determining the composition of the early crust could be addressed by orbital spectroscopy. Although both gravity and spectroscopic data have already been collected from martian orbit to some degree, we concluded that new missions carrying instruments specifically designed to address the above two investigations would be transformative compared to current knowledge, measurement precision, spatial resolution, and spectral resolution. Other methods of addressing these two investigations are possible, such as with a landed seismic network (PE1) or a rotorcraft with a suite of spectrometers (PE2). These concepts were deemed to be less immediately feasible compared to orbital gravity and spectroscopy but should be considered for ongoing technology development, and future missions.

The InSight mission detected endogenic seismic activity, revealing present-day tectonic, and possibly volcanic, activity (e.g., Giardini et al. [2020]; Sita and van der Lee [2022]; Kawamura et al [2023]). Characterization of this geological activity (PE3) would build off the InSight results and could be addressed with a landed heat flow probe–filling a gap left by InSight–or with interferometric synthetic aperture radar (InSAR) instrumentation from orbit (considered medium feasibility, due to either the need for a landed instrument to penetrate the surface, or the potentially costly orbital sounding instrumentation, see Section 8.6).

The SAG identified three additional investigations within the Planetary Evolution objective. We emphasize that all three of these investigations are also scientifically compelling, but are considered lower precedence, in a relative sense, to the investigations above because of the breadth of the science enabled, the feasibility of mission concepts, or both. These investigations are:

PE4: Characterize the geophysical properties and geological evolution of the martian dichotomy boundary.
PE5: Constrain the history of the martian core dynamo.
PE6: Quantify the impact bombardment history at Mars.

The dichotomy boundary delineates the biggest geological feature on Mars, separating the northern lowlands from the southern highlands. The boundary itself is a compelling location for high-resolution study, as it may coincide in places with the shorelines of an ancient ocean and represents an important feature in understanding the broader global dichotomy. Regional or local characterization explicitly focused on the boundary itself (PE4) would complement the global view of crustal structure, composition, and evolution addressed by investigations PE1 and PE2. This investigation could be addressed with a rotorcraft at, or near, the dichotomy boundary with a suite of geophysical and geological instruments (visible cameras, spectrometers, gravimeter, magnetometer). The history of the core dynamo (PE5) is key to understanding martian interior structure and early geophysical evolution but is uncertain, with questions about the initiation, cessation, and possibly intermittent timing of the dynamo still debated (e.g., Mittelholz et al. [2020a]). A rotorcraft that measures the planetary magnetic field at various altitudes and the magnetization of rocks in particular basins and lava flows could reveal this core dynamo history. We considered the first two investigations on these topics (PE4, and PE5) to be scientifically compelling, but feasibility of the associated mission concepts in a low-cost program was less certain compared to the orbiters associated with investigations PE1 and PE2.

Finally, we identified a sixth investigation to quantify the impact bombardment history at Mars (PE6). We considered this of lower precedence compared to the other investigations. Compiling an inventory of large impacts is highly feasible using orbital gravity data at Mars as has been done at the Moon [Neumann et al., 2015], but translating this inventory to an absolute chronology requires the ability to date samples, which we considered unlikely to be feasible in a low-cost program. Here, as well as for other lower science priority investigations, we did not provide a rigorous feasibility assessment, as it was seen as unlikely that such missions would be flown in the coming decade.

All six investigations in Planetary Evolution and their associated mission concepts have ties to the goals and investigations of other objectives. For example, a gravity orbiter flown to

characterize crustal structure could also be used to study time-variable gravity associated with seasonal and secular volatile fluxes (i.e., Recent Climate Evolution, Section 5.3, or Dynamic Modern Environments, Section 5.4), if operated over sufficiently long timescales. A dynamo-generated magnetic field in early martian history may have implications for surface habitability during the earliest parts of planetary history (Early Environmental Change, Section 5.2). Rotorcraft designed to study the dichotomy boundary or history of the core dynamo may also elucidate volcanic processes or ocean history. This interdisciplinary nature is a potential strength of a Mars program: focused, low-cost missions designed to address a particular investigation are very likely to enable results and open new inquiry in other objectives and investigations, maximizing scientific return.

5.2 Objective: Early Environmental Change

We identified Early Environmental Change (EE) as a major objective that could be addressed with low-cost Mars missions, representing the overarching goal to *understand the processes that drove habitability and climate change on early Mars as recorded in the ancient stratigraphic record*. The surface of Mars has remarkably ancient features, providing a unique opportunity within the Solar System to examine Mars' early climate and habitability during the first billion years of its evolution [MASWG, 2020]. Advances in this area would have applications to understanding the evolution and habitability of terrestrial planets more broadly [Ehlmann and Edwards, 2014]. Understanding Mars' ancient environments is essential to determining if Mars was once habitable, and what locations are the most promising to search for records of ancient life, in addition to providing a context for examining the early climate and geological evolution of any terrestrial planet more broadly. For these reasons, Mars' ancient environments have been a focus of many prior Mars missions, and the large number of still outstanding questions regarding ancient environments provide motivation for this objective to continue to be a focus of future Mars exploration and to be part of a future low-cost Mars program. We identified four main scientific investigations under the Early Environmental Change objective, including two investigations of high precedence:

EE1: Characterize the nature and timing of ancient aqueous deposits and major environmental transitions on early Mars.

EE3: Determine the nature, distribution, preservation, and sources of organic matter on ancient Mars.

Characterizing ancient aqueous deposits and major environmental transitions (EE1) includes both investigating geological landforms related to early Mars aqueous activity and examining the geology and mineralogy of the Noachian stratigraphic record. An example of an outstanding research question is whether or not early Mars had oceans, and missions in support of EE1 could study the morphology and mineralogy of ancient fluvial deposits along the dichotomy boundary (see, also, PE4) or in other major depositional basins. Missions under EE1 could also map mineralogical transitions in ancient Mars sedimentary deposits to better understand their links to climate cycles [Calvin et al., 2020] or groundwater flow [Horgan et al., 2021] and, more broadly the nature and cadence of environmental change on early Mars. Mission supporting EE1 could include high feasibility orbital concepts with a global focus, such as orbital

high-resolution spectroscopy and imaging (see, also, PE2), or more localized missions such as a rotorcraft investigation of fluvial features (e.g., deltas and shorelines) along the dichotomy boundary, although these mobile landed missions require additional technology development and cost reductions that put them in the low feasibility category.

Determining the nature, distribution, preservation, and sources of organic matter on ancient Mars (EE3) requires measuring the abundance and detailed composition of organic matter in ancient materials. Mission concepts include a lander for chemical analysis including characterization of organic matter to determine biotic or abiotic synthesis. Simple measurements could be obtained with small landers (low to medium feasibility), and such missions would help determine if signatures of past life are preserved in ancient habitable environments, a very high science priority for Mars investigations.

The SAG also identified two investigations of lower precedence within the Early Environmental Change objective:

EE2: Determine the controls on early habitability on Mars.
EE4: Constrain the earliest stages of Mars atmosphere evolution.

Mission concepts aiming to determine controls on early Mars habitability (EE2) would focus on sites where ancient liquid water-related features and hydrated minerals are present. The climate, surface physical and chemical conditions, and surface and/or subsurface water inventory (liquid and/or ice) of early Mars are the main parameters constraining the early habitability on Mars. Mission concepts for EE2 include in situ chemical, mineralogical, stratigraphic, and textural measurements to determine the timing and duration of diverse ancient habitable environments. This could be best achieved by rover and/or airborne missions (low feasibility) and, secondarily, by a subsurface sounder for structure (medium feasibility).

The mission concept considered for constraining the earliest stages of Mars atmosphere evolution (EE4) utilizes a lander to sample the Mars atmosphere and measure trace gas species and isotopes. Such measurements could provide insight into the relative sources and sinks prevalent in the early Mars atmosphere and help elucidate if Mars' atmosphere is primordial (primarily derived from the solar nebula) or secondary (outgassed from the interior).

Overall, Early Environmental Change investigations would build on the success of prior missions to answer high-priority science questions regarding early Mars habitability and climate. Prior orbital Mars missions such as the Mars Reconnaissance Orbiter (MRO) and Mars Express illustrated the capability of global observations for identifying regions of interest for ancient habitability, leading to new, higher-resolution orbital campaigns and local in situ investigations of landforms and the processes that created them.

The investigations in Early Environmental Change have complementary ties to the other objectives as well. For example, a rotorcraft tasked with investigating fluvial features and shorelines along the dichotomy boundary could also measure the dichotomy's crustal structure, which is directly relevant to Planetary Evolution (specifically, PE4). Understanding Mars' ancient climate and habitability will also require a better understanding of atmospheric and climate processes studied under Dynamic Modern Environments, Recent Climate Evolution, and Modern Habitability, and could contain overlapping studies and regions of interest. Early Environmental Change investigations are also essential for the upcoming human exploration strategy, as regions

on Mars that may have been habitable in the past, or contain signatures of ancient organic matter, are high-priority targets for human exploration. Overall, the Early Environmental Change objective provides a unique opportunity to study early planetary habitability and climate and to determine if Mars once harbored life.

5.3 Objective: Recent Climate Evolution

We identified a Recent Climate Evolution (RC) objective to understand modern volatile transport and the drivers of recent climate change using ice records and atmospheric reservoirs. The Amazonian period (covering the last ~3 Gyr) is generally characterized by a cold and dry climate due to Mars having a relatively thin atmosphere with limited greenhouse forcing [Jakosky et al., 2017], favoring solid ice as the predominant water phase [Hecht, 2002; Clifford et al., 2010]. Progress over decades has revolutionized our understanding of the global inventory of this ice, including at both poles (e.g., Byrne [2009]) and in the shallow subsurface at mid-latitudes (e.g., Feldman et al. [2004]; Morgan et al. [2021]). However, fundamental knowledge gaps remain. Although we expect that the ice's history is largely controlled by variations in Mars' orbital and rotational parameters through time [Jakosky and Carr, 1985; Head et al., 2003; Laskar et al., 2004], exactly how the stratigraphic record of these ice deposits reflects these variations remains debated. Relatedly, the age of the ice deposits, their present-day stability and relationship to atmospheric reservoirs, and the presence of any subsurface liquid in the ice at depth are uncertain. We identified two high precedence investigations under this Recent Climate Evolution objective that address these questions:

RC1: Determine how Mars' climate has changed over orbital time scales as recorded in global ice stratigraphies.
RC2: Constrain recent climate change on Mars.

Measurements of the distribution, structure, volume, variation in dust content and composition of global ice deposits from orbit are imperative to help provide us with a better understanding of Mars' climate history (RC1). Furthermore, characterizing these ice deposits will be essential for planning future robotic missions (e.g., MLE) and for identifying possible resources for crewed missions to Mars. While large-scale studies [Putzig and Morgan, 2022; Morgan et al., 2021] have attempted to determine the distribution of ice at relatively coarse spatial resolution, critical gaps in horizontal and vertical resolution remain for trying to determine global ice stratigraphies and distribution. These global-scale questions can be effectively addressed using orbital measurements (high feasibility). An orbiter with a sounding radar could characterize the ice deposits' distribution, internal structure, volume and, to some extent, the composition/dust content of the ice globally [I-MIM MDT, 2022]. For areas where ice is exposed at the surface, a high spatial resolution (meter-scale or less) VNIR spectrometer can constrain the dust content and potentially the grain size of the exposed ice (e.g., Khuller et al. [2021a]; Pascuzzo et al. [2022]). A TIR imager can also be used to constrain the near-surface depths of the ice, provided the orbital data is taken during local night (e.g., Bandfield [2007]; Piqueux et al. [2019]).

More recent ice deposits also provide a valuable record of recent climate change on Mars (RC2), but relatively little is known of the vertical structure or stratigraphy of martian ice deposits, especially at the fine-scale (centimeter to a few meter) resolution required to accurately

characterize how layers form within these deposits, and what layers represent in terms of accumulation, ablation and climate histories [Hvidberg et al., 2012; Smith et al., 2020]. In situ measurements of the detailed structure (layer thickness and physical/electromagnetic properties) and composition (dust abundance/chemistry, ice isotopic/bulk composition) of polar or mid-latitude ice would provide important constraints and information on the formation and evolutionary history of these climate-recording ice deposits. Some of these high-priority measurements could be conducted using simple landed missions (medium feasibility).

The remaining four investigations under the Recent Climate Change objective are of lower precedence than the previous two:

RC3: Determine the age of martian ice deposits.
RC4: Determine the presence or absence of near-surface liquid water within ice deposits.
RC5: Determine the relationship of layers in ice stratigraphies to climate and atmospheric processes by characterizing seasonal volatile fluxes.
RC6: Determine seasonal and annual ice transport rates on Mars.

Knowledge of the age and history of the formation of martian ice deposits (RC3) provides context for the environmental conditions present during the major portion of Mars' history over the last ~3 Ga (the Amazonian epoch). However, the ages of the martian ice deposits spread across the mid-latitudes and the poles are currently unknown, and it is uncertain whether the deposits observed are indicative of one, or numerous, accumulation episode(s) of ice (e.g., Christensen [2003]; Madeleine et al. [2014]; Bramson et al. [2017]; Bapst et al. [2018]; Sori et al. [2022]). Determining the age of a martian ice deposit by studying the lithics present within the deposit via drilling, or directly by making geochronology measurements of the ice, and potentially trapped gasses within, will help reduce the uncertainty in predicting the age and origin of martian ice deposits, but these measurements likely require a landed or mobile mission with drilling capability or more advanced instruments (low feasibility).

It is currently debated whether or not ice can melt to produce near-surface liquid water (RC4) on Mars under present-day conditions [Ingersoll, 1970; Clow, 1987; Williams et al., 2008; Dundas et al., 2019], but this process has key implications for modern habitability, the evolution of ice in response to climate change, and recent aqueous processes and mass wasting (e.g., Dundas et al. [2019]; Dundas [2020]; Khuller and Christensen [2021]; Stillman et al. [2020]). In situ measurements of ice using microwave radar on a simple landed mission can be used to detect subsurface layering and the presence of near-surface liquid water (medium feasibility). The energy balance at the surface dictates the phase of surface and near-surface ice. However, the surface energy balance at mid-latitude ice locations is currently poorly characterized, with large uncertainties in radiative and turbulent fluxes, which are the two largest sources/sinks to ice phase change. Landed in situ missions that characterize the surface energy balance at mid-latitude ice locations will therefore help determine and detect ice phase changes from sublimation and/or melting to test competing hypotheses for ice and liquid water stability and formation on Mars (medium feasibility).

Linking martian ice stratigraphy to climate cycles requires a detailed understanding of how the layers within the stratigraphic record form and evolve (RC5), including seasonal cycles of deposition and ablation, compaction, and recrystallization [MEPAG, 2019; Smith et al., 2020].

However, it is uncertain how layers form within regions such as the polar layered deposits. In situ measurements of ice deposition/sublimation through visible/near-infrared images, along with measurements of the transport of heat, momentum, volatiles, trace gasses, and dust from the surface will help constrain the mass and energy fluxes of ice at the surface. While some of these measurements could be conducted using simple landers (medium feasibility), many of these measurements would be most effective if conducted over a full seasonal cycle, and so may require additional technology development to allow a lander to survive polar winter.

The accumulation and transport history of martian ices across the planet (RC6) is currently not well characterized or understood [Levrard et al., 2007; Smith et al., 2020]. Improved knowledge of this ice transport rate at present will help better understand the long-term formation and evolution of the martian climate record stored in the ice deposits at the poles and the mid-latitudes. Additionally, these ice transport rates can also help provide insights into the rate of atmospheric loss of CO_2 and H_2O to space over time. Monitoring global and regional mass fluxes and linking these fluxes to volatile transport and atmospheric processes using a long-term gravity orbiter (high feasibility) can help constrain transport rates.

5.4 Objective: Dynamic Modern Environments

The Dynamic Modern Environments (DM) objective relates to understanding the many active processes that operate in the atmospheric and surface environment of present-day Mars, driving geologic and atmospheric cycles and evolution. Observing such processes in action today provides critical constraints and validation for models of such activity, including extension to models of processes that have occurred through large swaths of martian history, and insight into processes occurring on other terrestrial bodies throughout the Solar System and beyond. The DM investigations all address processes that are time-evolving *in the present day*. To gain insight into the processes at work, it is therefore very valuable to make the same measurements at different times of sol, different seasons, different solar cycle phases, and under different dust storm conditions, in order to deduce the connection between “drivers” and “responses”. A long timeline of observations (continuous or otherwise) is thus vital for increasing statistical confidence in the mechanisms and relationships identified.

As noted above, understanding presently active processes on Mars is valuable for understanding how such processes operated in Mars’s past, affecting our interpretation of the rock and ice records of past Mars climate epochs, and our approach to the Planetary Evolution and Recent Climate Evolution objectives. Relevant geological records range from layering of dust and ice in the polar caps and mid-latitude subsurface ice deposits (see also, RC1, RC5) to evidence of past wind and aeolian regimes in rock abrasion features and sedimentary structures. Current models (e.g., Madeleine et al. [2014]; Naar et al. [2020]) do not replicate the observed distribution of subsurface ice deposits from past climate epochs; thus, characterizing past and present volatile and dust cycles (including the radiative effects of clouds and dust storms) is essential to understanding the distribution, structure, and stratigraphy of ice deposits that represent climate records on Mars. Further, studying modern atmospheric loss rates and their relationship to the solar cycle, crustal magnetism, and the dust cycle (which can greatly increase loss rates) provides insight into the causes of atmospheric loss over much longer timescales (see also, EE4).

Mars is an active target of future robotic and human exploration, and modern active processes pose particular risks to the safe arrival and operation of surface missions. Potential hazards to surface missions include: density, temperature, and wind variations during the entry, descent, and landing period; strong winds, or rapid density or wind variations during rotorcraft take-off, flight, or landing; reduced visibility and potential damage to optics and other spacecraft elements during dust storms or other major aeolian events, either mechanical or via electrostatic forces; and risks due to damage by dust or sand grains during surface operations. Dust also poses a major risk to solar-powered landed missions by reducing available solar power with time (the demise of the InSight mission is a contemporary, and pointed, example of this). Thus, an ability to predict relative rates of dust lifting and removal at any new landing site - as well as the timing of major dust storm activity - would be particularly valuable to conduct with future low-cost surface missions.

Investigations that fall under this heading would address key questions about modern surface/atmosphere evolution that have eluded answers to date. Importantly, the interrelationship between the myriad processes taking place on the surface and in the atmosphere (Figure 4) means that answering one question may have a significant impact on others. These questions are addressed by eight science investigations, discussed in more detail presently. Of these eight investigations, four are considered high precedence:

DM1: Understand the surface drivers of the dust and water cycles on Mars, including dust storms.
DM2: Understand atmosphere/climate variability including the timing of dust storms.
DM4: Determine how lower atmospheric dynamics influence atmospheric escape to space.
DM8: Understand and characterize the controlling factors for surface weather on Mars.

Major (regional and global) dust storms dominate weather and climate variability on present-day Mars but the main processes and feedbacks that produce such storms remain poorly understood (DM1). This is particularly true for the largest (i.e., global) storms (e.g., Newman and Richardson [2015]; Kahre et al. [2017]; Newman et al. [2019]). A key knowledge gap involves the mechanisms by which most dust is lifted, especially during dust storm onset, and how the rate of dust lifting relates to local atmospheric conditions and surface properties. The involvement of sand motion, electrostatics, and several other effects in triggering martian dust lifting is also unknown; limited progress has been made in observing dust lifting during storm onset [Lemmon et al., 2022].

Similarly, the water cycle on Mars controls the stability and formation of ice deposits at the poles and the mid-latitudes through time [Jakosky et al., 1997; Christensen, 2003; Montmessin et al., 2017], but the lack of measurements regarding the turbulent fluxes of wind, water, and temperature makes it difficult to constrain the energy balance of ice and potentially liquid water near the surface. Furthermore, the near-surface vertical distribution of water vapor on Mars, which plays a key role in ice and liquid water formation, stability, and evolution, is highly uncertain at present due to a lack of in situ water vapor profile measurements (e.g., Tamppari and Lemmon [2020]).

A hard-impact lander carrying sensors capable of relating dust lifting and surface-atmosphere water exchange to all relevant environmental drivers, such as wind stress, turbulent

and radiative thermal forcing, sand motion, electrostatics, and surface properties (e.g., roughness, soil moisture, grain sizes) could address this investigation (medium feasibility). The mission would target a low-latitude region observed to have significant local dust lifting.

Global measurement of thermal and aerosol/volatile atmospheric conditions at low and high altitudes, along with low-altitude wind patterns, are needed to address investigation DM2. Measurements here would extend the baseline of the existing data record, enabling identification of interannual variations. The first direct measurements of near-surface wind and the ability to observe the atmosphere at all local solar times would fill critical knowledge gaps [Read et al., 2017; MEPAG, 2019] allowing the role of dust or water transport to be separated from dust lifting and deposition or surface water exchange.

A climate orbiter with a thermal infrared spectrometer, weather imaging system and a wind speed/profile instrument would address this investigation (high feasibility), extending the existing long-term global record of diurnal atmospheric dust and volatile transport and temperature, with the addition of wind measurements to inform and constrain current atmospheric transport. An orbit that enables measurements at all times of sol (i.e., taking some number of sols to observe through the full diurnal cycle) would provide vital information on processes with large diurnal variability, such as cloud formation and dust lifting.

Atmospheric tides, gravity waves, and other waves propagating from the lower to the upper atmosphere (DM4) have a major impact on upper atmosphere densities, temperatures, and winds, which are important for understanding upper atmosphere chemistry and escape [Bougher et al., 2017]. Understanding escape rates on present day Mars, and their relationship to both solar forcing and transient phenomena such as dust storms, have implications for how the martian climate evolved over the recent and even more ancient past. A mission concept similar to that described for DM2 could address this investigation (high feasibility), with the further addition of a UV sounder to probe the upper atmosphere, covering a broader depth of the atmosphere (cf. MAVEN-IUVS).

We do not yet know if short-term, medium-range, or long-term weather prediction is possible on Mars in a similar manner to Earth [Navarro et al., 2017]. Several studies have demonstrated the value of atmospheric models assimilating orbital, global temperature/radiance data [Lewis and Barker, 2005; Lewis et al., 2007; Lee et al., 2011; Greybush et al., 2012; Holmes et al., 2020]. However, these models frequently diverge from each other—and from reality—by failing to adequately capture key weather features. More complete surface pressure data, alone, could provide a means of remedying this issue; a network of surface sensors may provide enough information to help models 'keep up' with evolving weather patterns (DM8). Further, simple temperature, 2D wind, and basic radiative measurements would offer a synchronous, multi-location, and time-evolving picture of the dust forcing and thermal response at key locations across the planet. Such networks would provide improved understanding of dust lifting and storms, aeolian processes, and near-surface atmospheric transport (high feasibility).

A network of several micro-landers (medium or lower feasibility) with basic meteorological and radiative sensors can be targeted to locations where surface meteorological data can most improve models and maximize predictive ability, in further support of DM8. However, assessing the final number and optimum locations of micro landers would require an Observing System Simulation Experiment (OSSE) to maximize the returned science [Reale et al., 2021]. Such a mission would also have benefit to the overall Mars Exploration Program by

offering weather and dust storm early warning and the potential for weather forecasting for future landed missions, including for human exploration.

The remaining four investigations under the Dynamic Modern Mars objective are of a lower precedence than those discussed above:

DM3: Understand the present-day water and CO_2 exchange between the atmosphere and subsurface.
DM5: Determine the location, rate, and nature of episodic, seasonal, and interannual surface changes.
DM6: Characterize the current systems in the martian ionosphere and magnetosphere.
DM7: Determine the rate and mechanism of modification of polar or aeolian landforms at high spatio-temporal resolution.

The deposition and sublimation of surficial ices (DM3) is thought to drive the evolution of multiple surface geological features, such as slope streaks [Lange et al., 2022] and several types of gullies [Diniega et al., 2021; Khuller et al., 2021b], under modern martian conditions. However, many details on the processes that generate the observed surface geomorphology remain unknown. These include the depth of frost accumulation in the regolith, how interbedding of volatile- and dust-rich deposits lead to the observed layers in the poles and mid-latitudes (see also, RC5, and MEPAG [2019]; Becerra et al. [2021]), the nature of water vapor exchange through the martian regolith [Savijärvi and Harri, 2021], and the near-surface distribution of water vapor in the martian atmosphere (e.g., Smith [2002]).

A small, landed spacecraft (medium or lower feasibility) could, if properly sited, simultaneously measure water vapor above, at, and below the surface, so as to track regolith-atmosphere exchange, while simultaneously measuring the atmospheric drivers influencing that exchange (e.g., T, p, wind). Seeking the presence of liquid water (brine) could also be accomplished using, e.g., dielectric measurements. These measurements would also contribute towards mission support and human exploration interests, such as ISRU planning and weather prediction. Near-surface wind data could feed into assessment of the potential for local transport of contaminants away from a human or robotic landing site, which is a concern for planetary protection.

Repeat, high-resolution images and spectra over active martian processes have provided a tremendous amount of insight into the timing and volume of surface activity under present-day conditions (DM5) [Diniega et al., 2021; Dundas et al., 2021]. Extending this type of long-term monitoring using repeat-pass medium/high-resolution images and spectroscopy on new, small orbiter(s) would further our ability to investigate and understand the processes that govern the formation of many martian landforms. An orbiter with a focus on repeat-pass medium/high resolution images and VNIR spectroscopy on diurnal/seasonal timescales with potentially an altimeter could accomplish this investigation (medium feasibility).

Currents couple the solar wind to the ionosphere through the martian magnetosphere, and therefore transfer the energy that control upper atmospheric properties and escape (DM6). The magnitude and direction of this current has not been directly measured at Mars before and is instead inferred from magnetic field measurements. Using magnetic field perturbations from single flybys to infer currents requires unverified assumptions about how the magnetic field near

(but not sampled by) the spacecraft varies spatially [Brain et al., 2020; Mittelholz et al., 2020]. Using magnetic field statistics enables only an average picture of current configuration, and results in low spatial resolution [Ramstad et al., 2020].

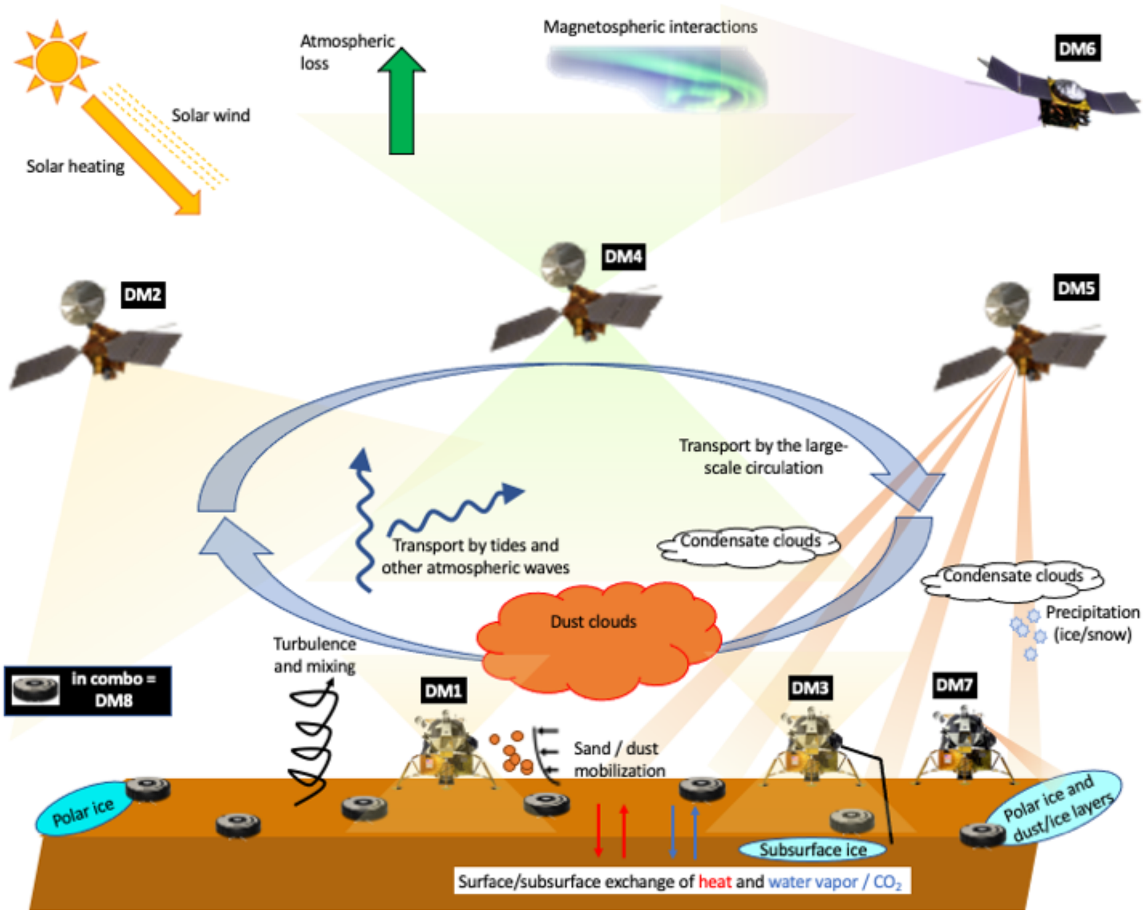

***Figure 4**: Key processes relevant to Dynamic Modern Environments (DM) and indication of how the DM investigations would study them.*

An orbiter with vector electric field and vector magnetic field instruments could address DM6 (medium feasibility). The spacecraft's orbit would ideally span altitudes from the main peak of the ionosphere (~120 km) out to the bow shock (> 2000 km) and distant magnetotail (> 6500 km); however, an orbit that focuses on altitudes from the exobase (~200 km) to the induced magnetosphere boundary (~1500 km) would also make significant forward progress. Supporting plasma measurements would also be helpful.

Numerous surface geological features such as gullies, dunes, and recurring slope lineae (RSL) are being modified under present-day conditions, based on orbital visible images. However, the lack of high spatio-temporal resolution images of these locations has made it challenging to decipher what causes for the formation and evolution of these features, with debates on the roles that ices, liquid water and wind play in their formation and modification [Diniega et al., 2010, 2021; Chojnacki et al., 2011; Dundas et al., 2012, 2019; Stillman et al., 2020; Khuller and Christensen, 2021]. Addressing this investigation (DM7) would require a small lander (or series of small landers) targeting specific landforms that can be reached without precision landing (medium feasibility). The lander and its payload would also need to survive extreme conditions if

operating through the martian winter. The payload may include a visible/near-infrared camera to detect mass-wasting/movement and basic meteorology data to characterize near-surface energy balance along with potential volatile phase changes, with high spatio-temporal resolution so as to provide a continuous timeline of the processes involved in the formation of modern active geological features.

5.5 Objective: Modern Habitability

The Modern Habitability (MH) objective centers around the search for currently or recently habitable environments and present-day life on Mars. The search for life remains a top priority for NASA science over the next decade, and Mars provides a critical data point in the search for both ancient and modern biosignatures. The Mars Extant Life: What's Next? workshop found that the deep subsurface, salts, and ices can provide modern habitats where extant life may be found [Carrier et al., 2020]. Whether or not life existed or still exists in these currently habitable environments on Mars will help frame expectations about the potential for life elsewhere, search strategies, and the development and maturation of search-for-life instrumentation. Additionally, understanding habitable environments on Mars can improve understanding of early prebiotic chemistry and carbon cycling in an extraterrestrial environment. Measurements relevant to the search for life and habitability include characterization of organic material and determining the presence and variability of liquid water, salts, redox energetics, organic molecules, and astrobiologically relevant gases. We have identified four compelling scientific investigations under this objective, including two investigations focused on life and biosignature detection, and two focused on habitability (Figure 5), including one high precedence investigation:

MH1: Search for currently habitable deep subsurface environments on Mars.

In the search for modern/extant life, accessing the deeper subsurface where liquid water could be stable will be crucial to accessing habitable modern ecosystems where the harsh surface conditions are minimized (e.g., desiccation and radiation). A first key investigation to better understand the habitability and likelihood or extant life in the subsurface today would be to confirm or refute the hypothesis of a global deep aquifer on Mars (MH1). One approach to this investigation is through subsurface sounding on a lander, such as via active time-domain low-frequency electromagnetic (EM) sounding or passive low-frequency (EM) sounding (i.e., magnetotellurics; Grimm et al. [2007]; Aboud et al. [2014]). This investigation (medium feasibility) would also provide significant geological and hydrological insight into the nature of the martian subsurface, the martian water cycle, and the persistence of water on Mars over time.

Much of the SAG's deliberations under this objective focused on whether or not life detection missions would be possible under a low-cost program, or if such a program should focus on habitability investigations to provide context for higher-cost and broader scope life-detection missions like MLE. However, there was genuine enthusiasm for keeping life detection within the scope of the program given the significant progress that has been made in life detection technology in recent years and the critical importance of life detection as the next step for astrobiological investigations at Mars. Thus, we developed the following three investigations covering additional areas of habitability and life detection science:

MH2: Search for evidence of present-day life near Mars' surface.
MH3: Constrain the source location and origins of potentially biogenic gases.
MH4: Search for currently habitable shallow subsurface environments on Mars.

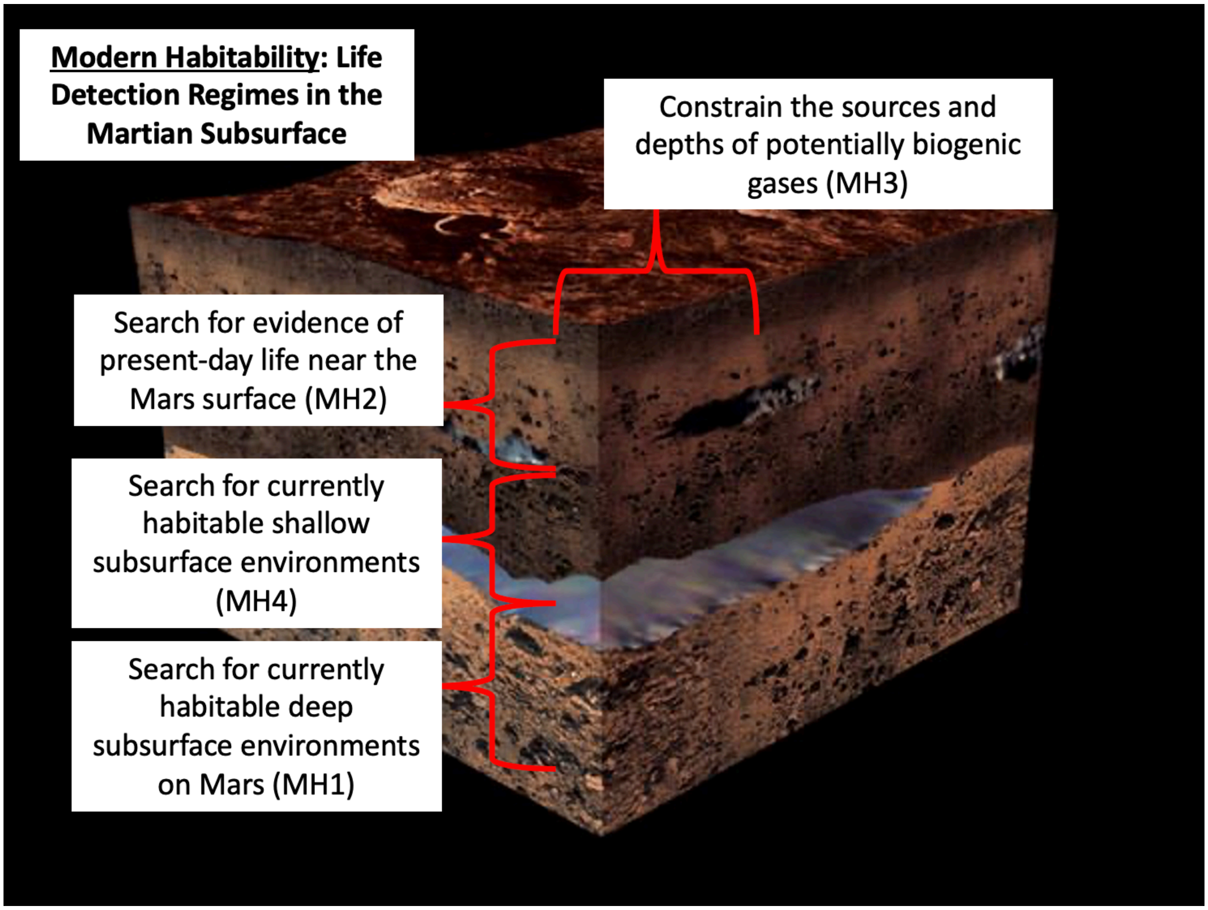

Figure 5*: Overview of modern habitability investigations for Dynamic Mars.*

Critical measurements for the search for life in near-surface habitats (MH2) include organics characterization (bioenergetic potential, CHNOPS, and inventory of organics including lipids, amino acids, pigments, and macromolecular organic material), as well as determination of the source (biotic vs. meteoritic infall vs. abiotic in situ reaction products) of organic material. Radiation exposure likely means that cellular communities are not viable at the surface, so a true life-detection mission would likely require a lander with some form of subsurface access, such as either a meter-class drill or impact excavation. Because of the complex technical requirements of such a mission, this investigation was ranked as low feasibility, but with the hope that additional technology development would make it more feasible in future years.

The high-cost bias that has existed for life detection payloads and missions historically attempts to take a large percentage of the aforementioned capabilities together with typically low to moderate starting TRL, which extends the mission formulation duration. Traditionally, these new capabilities in the habitability realm have been reserved for Flagship-class missions (e.g., SAM, CheMin, SHERLOC). The MCE-SAG has concluded that the search for microbial life, cells, and intact or lysed cellular features could potentially be performed with small payloads,

deployed as a buildable strategy with collection of additive measurements, as with other physical science disciplines. These measurements can be achieved by reducing the scope of life detection instrumentation (e.g., GC-MS, LD-MS, Raman, fluorometer) but not fidelity, to enable measurement of specific life detection parameters while reducing overall cost per investigation. Search-for-life measurements should include the versatile chemical building blocks of life, complex, multimeric biomolecules, containment structures, and function-specific molecules. Combined, these classes of indicators could provide compelling evidence of life. Moreover, if these investigations needed to be separated due to cost, there would still be noteworthy geomicrobiological observations that can be carried out. The ability to make these measurements in a piecemeal approach (i.e., 1-2 instruments as part of the low-cost astrobiology portion of a payload) or a full suite of lower-scope measurements (i.e., a complete low-cost astrobiology payload with geochemistry and atmospheric tools for organic chemistry and potential biogenic gases, respectively) makes life detection studies viable in a low-cost program. There now exist new avenues to advance TRL of prospective habitability payloads through suborbital, ISS and small satellite means.

The MLE concept study examined in *OWL* demonstrated the viability of reducing payload mass and functionality for life-detection instruments by showing that the Sample Analysis on Mars (SAM) experiments from the Mars Science Laboratory can, today, be similarly achieved with smaller, simpler instrumentation while still providing ample measurable features that are improvements to the original SAM payload [House et al., 2022].

Life detection measurements should be taken across the so-called “confidence scale” as laid out in the 2022 “Community Report from the Biosignature Standards of Evidence Community Workshop” [Meadows et al. 2022] produced by the Network for Life Detection, with prioritization of the highest-confidence measurements. One of the key knowledge gaps in the search for martian life is the definition of an “abiotic baseline” of organic molecules. It should be expected that there are multiple types of abiotic synthesis, unknown or known biotic synthesis, and active diagenetic processes that may work to degrade and/or alter organics (e.g., radiation, oxidation). Biosignature measurement requirements should encompass potential pools of organics and consider the likelihood of a low concentration and heterogeneous distribution of biosignatures as well as potential analytical interferences in detection strategy. Other knowledge gaps include the abundance of light elements, characterization of the structures in more refractory phases of organics, and spatial and bulk analyses of water/ice including permeability and the porosity of the rock material.

In the search for preserved molecular evidence of life, radiation protection increases with increasing depth over the meter scale, so the even the shallow subsurface (up to several meters depth) is of major interest for both habitability and extant life investigations (MH4). The leading indicator for habitability is the presence of stable liquid water. Upon successful subsurface detection, investigations dealing with potential water activity would be the most critical component for both habitable subsurface environments as well as cellular (i.e., active/extant) life detection.

Recent observations of mid-latitude ice have shown that this ice is retreating (e.g., Byrne et al. [2009]; Dundas et al. [2018]; Khuller and Christensen [2021]), but it is currently debated whether this ice can melt (rather than sublimate) in the shallow subsurface under present-day and modern martian conditions (see also, RC4) [Ingersoll, 1970; Clow, 1987; Williams et al., 2008;

Dundas et al., 2019]. Whether or not there is near-surface liquid water has key implications for the potential for extant martian life, and the formation of present-day mass-wasting landforms such as mid-latitude gullies [Dundas et al., 2019; Khuller and Christensen, 2021] and recurring slope lineae [Dundas, 2020; Stillman et al., 2020] (see also, DM5, DM7). Relatively shallow thicknesses (< ~2 m) of H_2O ice can protect underlying organisms from ionizing radiation over ~40,000-year timescales [Dartnell et al., 2007], so these locations might be favorable for any extant life, particularly if near-surface liquid water is available. The near-surface location of mid-latitude ice deposits that might be melting near the surface provides an attractive location to search for extant, or recently active, microorganisms.

Missions under both MH2 and MH4 would not duplicate the efforts of a New Frontiers-class MLE-like mission. The former could provide reference measurements of desiccation and UV-C exposure at the surface to be used as contextual information for a set of higher fidelity measurements of the deeper subsurface conducted by the latter. Rather, these and other measurements relevant to the search for life that can be achieved with smaller payloads could help to augment or prepare for MLE. For example, smaller payloads could enable more rapid, targeted exploration of multiple regions of interest to deduce habitable conditions (e.g., water activity, redox gradients, salt content, soil conductivity, total organic carbon) and search for specific molecules relevant to life by using miniaturized instruments and targeted sensors. This sort of a priori knowledge about the broader habitability of the martian subsurface would be important given that MLE is slated to be a stationary lander.

For both MH2 and MH4, environments slated for future human exploration should be given higher priority for robotic characterization, especially those in which habitable conditions may exist in the shallow subsurface, to rule out the presence of authigenic modern biota before human exploration occurs, both because of the possibility of contamination from human presence, as well as potential hazards such lifeforms may pose to the health and safety of human explorers. Opportunities to conduct investigations of such environments are thus critical in the near and mid-term. Planetary protection protocols in which potential martian habitats and experiments would be conducted in close proximity to astrobiological targets (e.g., former lacustrine sediment settings, within craters where preserved lakebed sediments exist, close to RSL sites) will require updates.

The atmosphere may also serve as a repository for biosignatures in the form of biogenic gases, such as methane. The abundance and distribution of methane on Mars remains a highly debated subject (e.g., Yung et al. [2018]; Knutsen et al. [2021]; Giuranna et al. [2021]) but has the potential to provide major insights into ongoing biological and geological activity on Mars. A single lander or network of landers designed to make rapid, accurate measurements of the abundance of potentially biogenic gases like methane (MH3) at the surface of Mars at hourly to annual timescales could help resolve many outstanding questions (medium feasibility). Such a mission would also benefit from wind measurements to help further pinpoint the source (see also, DM8).

6. Recommended Path Forward for Low-Cost Mission Program

6.1 Envisioning an AO for a Low-Cost Program

The group carefully considered the level of guidance or degree of constraints that were desirable for a low-cost mission program. A competed program was determined to be ideal, as it would offer the greatest ability to adapt to recent science discoveries and engineering developments, encourage proposers to be creative and inventive, and would likely result in a wide range of science investigations being conducted. However, putting out an AO that simply required proposals to address a high-priority science question from *OWL* or the MEPAG Goals document would place the entire onus on the program manager(s) — at least, after missions had been assessed by review panels for science and feasibility — to decide the path of this portion of the MEP. The MCE-SAG group discussed that this approach could hinder the maintenance of a cohesive program for future Mars exploration, and work against the programmatic aims of the MEP.

As a counterexample, planned missions to the lunar surface under the Commercial Lunar Payload Services (CLPS) program, using payloads selected through Payloads and Research Investigations on the Surface of the Moon (PRISM) calls, have seen increasing flexibility in successive AOs, allowing for a variety of site-specific investigations that do not necessarily hew to high-level scientific goals. The Decadal Survey (Chapter 22, 'Structuring LDEP to Achieve Decadal-Level Science'), however, finds benefit in maintaining high-level coordination of science goals and measurement objectives for a lunar program, and specifically identifies the success of the MEP as an exemplar in this area. The MCE-SAG wishes to maintain this same type of programmatic structure in a low-cost program, such that it seamlessly integrates into the current framework of the MEP and follows recommendations in the Decadal Survey.

By identifying five broad objectives that cover the full range of Mars science, prioritizing science investigations within each of them, and then demonstrating the strong interconnectedness of those objectives and investigations via the "Braided River," the group established clear constraints on, and a limited set of objectives for, a low-cost program. However, the descriptions of investigations included herein are focused on the key science questions that each investigation should address, rather than mission specifics. Proposers would thus retain significant flexibility in terms of the actual mission concepts, with no specification of mission type, design, or specific technology.

The envisioned AO would require that proposers address one (or more) of the listed investigations with their mission, where the investigations may lie within one objective or cross multiple objectives. This "menu" approach is similar to that of the New Frontiers selection process in many respects, except that investigations need not be removed from the list after being addressed by a mission (unless it is determined that such a mission fully addresses the underlying scientific question—likely a stretch for a low-cost mission). The list of investigations could, and should, be reviewed periodically. Further, an AO might require that proposers discuss both scientific linkages to past missions, and also viable pathways forward for future missions. In this way, the concept of the "Braided River" is preserved, by ensuring missions have some level of connectedness, and are not stand alone "islands".

As the program progresses, each AO would remain open across all five objectives, as all areas would have key science objectives that could be addressed with a small mission. But evaluation of proposals could consider the latest science priorities (impacted by recent discoveries) and technology and are not constrained to following the path of a single objective. This flexibility removes dependencies between potential selected missions and enables a consistent advancement in Mars and planetary science, within potentially several science areas, during the program lifetime.

6.2 Promote Technology Development to Get the Best Possible Science

As noted above, a difference of the lunar small-mission program is the lack of any top-level programmatic science theme may lead to unfocused priorities for science teams and technological development. By contrast, the low-cost program developed by the MCE-SAG would focus both on a clear—albeit diverse—set of investigations that align within a singular theme and reflect current science priorities. NASA centers, academic labs, and industry partners would have a focused "menu" describing where scientific and engineering expertise, hardware, and funding should be directed, in order to be in best positioned for having their proposed mission(s) selected. Similarly, instrument and vehicle technology development programs (e.g., PICASSO, MatISSE, etc.) or future technology development efforts (e.g., autonomy, computing and avionics, etc.) could consider the needs of this program when assessing funding proposals. The benefit to NASA is both greater efficiency and reduced cost.

Equally, there are major benefits to keeping the range of investigations broad. Under the five objectives identified in this report, no high science value investigation is completely omitted due solely to perceived current or near-future technical readiness, as future (unknown) developments may advance the technical readiness and feasibility beyond the present-day assessment. This approach allows proposers to either react to technological advances, or work toward such advances themselves, on missions judged by the MCE-SAG to be low feasibility at the time of writing.

6.3 Enabling a Mars Program with the "Braided River" Approach

The beauty of the Braided River approach is that it enables the filling of major knowledge gaps within a clear, cohesive, and inspiring program. The five objectives—Planetary Evolution, Early Environmental Change, Recent Climate Evolution, Dynamic Modern Environments, Modern Habitability—are coupled and interconnected via the overarching "Dynamic Mars" theme. Change on Mars, as evoked by the thematic term 'dynamic,' covers a continuum of timescales, throughout Mars' past, present, and future. We can observe the history of past processes (such as climate evolution) in the ice and rock record of Mars. Yet, understanding the operation of processes in Mars's past is greatly enabled by making observations of such processes on present-day Mars, where we can measure both the "driver" and "response," formulate and refine theories and models, and test them against new data. Similarly, learning how present-day Mars works enables not only safer, cheaper future robotic and human exploration of Mars, and future Mars science discoveries, but also extends far beyond Mars to a better understanding of our own planet, other planets in our Solar System, and those still to be explored elsewhere. In

combination, the Dynamic Mars program will make progress toward gaining an understanding of Mars that approaches that of Earth—the system we know best—and inform us about terrestrial planetary systems in general.

A key component of the Braided River approach is the ability to stay within a single, overarching theme, "Dynamic Mars," without being constrained to follow a single path or (crucially) to require results from an earlier mission before the next is selected. Figure 3 shows many example pathways that connect the investigations (blue lines), both within and across objectives, all while remaining under the Dynamic Mars umbrella. For example, one might begin by following a pathway from one opportunity to the next within the same objective, or by transitioning to another objective. There is no 'correct' path to follow; missions should be designed (and selected) based upon the current state of the science, how the present mission links to findings and questions addressed by prior missions, and how it affords opportunities to resolve larger questions with future missions. In this way, the braided river ensures continuity within the program—missions are not 'one-offs,' but part of a larger, linked program. With this concept, the MEP remains cohesive and inspiring for decades to come.

7. Technical and programmatic considerations

7.1 Technology Assessment Summary

Three general classes of low-cost Mars missions were identified in the MCE-SAG discussions. The first class are orbital missions. These are viewed as feasible with current technology within a Discovery cost cap (~$500M) as well as, in many cases, for SmallSats and possibly CubeSats with costs well below the Discovery cap. The second type of mission is the hard lander (such as the SHIELD concept described in Section 7.3.4). These missions, designed to reach the martian surface without parachute, thrusters, or landing systems, are, likewise, expected to fit within the Discovery cost cap (and smaller hard landers may be much lower in cost). However, the technology is still several years away from being mission ready. This is true of the landing technology, itself, as well as many instruments anticipated to be able to handle the high g-loads of a hard lander. The current generation of soft landers (e.g., InSight), making up the third type of mission, have costs that are, at present, too high to fit within even the current Discovery cost cap. In a broad sense, advancements in in soft EDL technology can perhaps reduce the costs within a decade to allow for soft landing options in a low-cost environment.

For landed missions, a significant cost driver arises for those missions that need surface access (e.g., sample collection or instrument deployment) and especially direct sub-surface access (drilling). Relatively simple, modest deployment devices and simple drills may be possible; however, complex robotic arms and meter-scale (or deeper) direct penetration methods are not currently within the cost range for a low-cost mission. Mobility on the surface is another large cost driver due to increased complexity of the spacecraft. *Ingenuity*-style helicopters appear possible within the notional low-cost, cost cap only with very modest payloads. Slightly larger designs with significantly more range and/or instrument payloads may be possible with additional technology development.

There are two further technology and cost challenges, especially for the smallest missions. The first is getting to Mars (either into orbit or to the surface), The second is getting the data back to Earth from Mars. These challenges will be discussed further below.

7.2 Mature Technologies and Instruments Ready for Deployment

There are several low-cost missions that were identified as of high or medium scientific priority where the technology is available to build and fly them now or with minimal technology development (i.e., high feasibility; see Section 4.3 and Table 2). As noted above, all of these are presently orbital missions, and they cover four of the five scientific objectives. There are a broad range of instruments that fit into a low-cost mission (by mass and cost) that have either already flown (although not necessarily to Mars) or are currently of high heritage and ready for a mission development (see Appendix 6, Table A6.1). The instruments and instrument suites range from those that might (almost) fit on a CubeSat, to many that require a larger-scale SmallSat, to still others that require something closer to a Discovery-class mission.

There are over 40 instruments or measurement techniques enabling the identified investigations that can reasonably (cost and mass) fit on a low-cost orbiter mission (Appendix 6).

Almost 30 such instruments are ready for a flight mission proposal at present. These are either reflights of existing instruments, high heritage designs from existing instruments, or sufficiently mature concepts (i.e., TRL 6) deemed ready for a mission proposal.

Depending on the mission class/risk posture and mission size, complexity, and the number of instruments on the orbiter (see, also, Section 8), many of the proposed investigations could be ready for launch in very short order. Many of the instruments, along with a suitable orbital spacecraft bus, are mature technologies ready to rapidly move into Phase C/D.

7.3 Technology Development Needs and Benefits

7.3.1 Astrobiology Technology for Life Detection

Considerable improvements have been made in technologies for the search for life over the last 20 years, including high-TRL spectrometers and payload suites previously flown to Mars that have since been miniaturized, mid-TRL sample processing and analytical instruments designed particularly for life-search applications, fundamental biology and astrobiology payloads flown on Earth-orbiting CubeSats and aboard the International Space Station, and technology developed for human health, performance, and safety instrumentation. Additionally, there are numerous relevant instruments slated to fly as Commercial Lunar Payloads over the next several years. Thus, there are numerous mid- to high-TRL instruments poised for inclusion on future low-cost payloads. Additionally, there are a number of robust, commercial off-the-shelf (COTS) sensors that could be tested for utility on future life-search missions.

Subsequent testing would need to be done to ensure instrumentation could survive potentially difficult landing scenarios (e.g., a rough or hard landing). In many cases, contact with, and/or manipulation of, surface material will be required to achieve successful detection, particularly in the case of the analysis of organic matter. Relevant architectures identified that should be further explored for life detection application include distributed sensor networks, rough-landing impactors and subsurface probes, small ride along payloads, and rotorcraft. These architectures fall later on the mission timeline (see Braided River, Section 4.4), and reflect their more sophisticated nature, both in instrumentation and in operation, but hold potential for introducing a more buildable strategy to the search for life on Mars. To enable such measurements, however, requires immediate investment in the requisite technologies such that they become viable instruments for the low-cost program in a reasonable timeframe, as recognized in the *OWL* Decadal Survey.

There are several small instruments and technologies suitable for making useful in situ astrobiology measurements on the martian surface. These measurements could include observing the variability of biologically relevant gases, characterization of organic matter in the near surface, and characterization of the local variability of liquid water, salt content, and redox energetics. This technology has become available in the last decade through the traditional NASA SMD/STMD pipeline of technology development, and from commercial industry; many have been flown on small fundamental biology or astrobiology payloads in low Earth orbit or aboard the International Space Station [Ricco et al. 2007, 2011; Nicholson et al., 2011; Ehrenfreund et al. 2014; Lewis et al. 2014; Matin et al. 2017; Park et al., 2017]. Leveraging what has been successfully deployed on the ISS for space biology applications in low Earth orbit would reduce

the cost of overall development with respect to spaceflight confidence and TRL maturity. Many of these experiments require processes that can be automated to enable fluid/sample movement between sensors, spectroscopic analysis, and the introduction of dyes, buffers, etc. Such automation may help offset the larger expense of these comparatively complex experimental techniques. Smaller, additive efforts for instrument analyses, in situ, can provide critical astrobiology data, especially for microbially favorable features in habitable environments, potentially helping to prioritize future sites of interest to the search for both extant and ancient life. An example of this would be water activity (a_w) for shallow subsurface martian sediments [Martín-Torres et al., 2015].

Distinguishing between habitability technologies, life detection capabilities, and biological validation can help map a technology roadmap for assessments of what the final data products of future small life detection payloads would need to be to ensure value for future New Frontiers or Discovery-class mission concepts (e.g., MLE). Moreover, the spatial resolution of measurements, if at the non-cellular level, can only provide limited, reliable information on potential biological processes in the martian subsurface or from collected samples in situ. Having the spatial capability of cellular resolution in addition to the spectral or chemical analyses would allow mission scientists to evaluate textural and spatial features to determine authigenic chemical biomarkers or physical biosignatures [Perl et al. 2021].

Examples of technologies and instruments relevant to future landed low-cost Mars astrobiology missions include, but are not limited to, carbon nanotube (CNT) and other gas sensors, electrochemical sensors for ions and organic carbon (total or classes of molecules), miniaturized gas chromatographs and mass spectrometers, miniaturized Raman spectrometers, micro-spectrometers, micro-LIBS, miniature tunable laser spectrometers, microfluidic devices, immunoassays, fluorescent dyes, miniaturized optical microscopes, and nanopore sequencers [Li and Lu, 2009; Gassensmith et al., 2014; Vitek et al., 2014; Meyyappan et al., 2015; Meyyappan, 2016; Snyder et al., 2016; John et al., 2016; Szopa et al., 2017; Johnson et al., 2017; Cao et al., 2018; Creamer et al., 2019; Trellu et al., 2019; Quinn et al., 2019; Noell et al., 2019; García-Descalzo et al.. 2019; Norizan et al., 2020; Koehne et al., 2020; Winiberg et al., 2020; Fairén et al., 2020; Carr et al., 2020; Maggiori et al., 2020; Clark et al., 2021; Košek et al., 2021; Edwards et al., 2021; Gasnault et al., 2021; Craft et al., 2021; Duca et al., 2021; Choi and Moses, 2022; O'Connor et al., 2022; Van Volkenburg et al., 2022; Estlack et al., 2023]. Many of these sensors have been flown previously on the International Space Station, are pending flight on future lunar missions (e.g., the MSolo mass spectrometer on the Volatiles Investigating Polar Exploration Rover—VIPER—mission) [Ennico-Smith et al., 2020], or are at TRL levels making them viable for flight in the short term.

To ensure fast infusion of this technology into the Mars program and compliance with the requirements imposed by a "hard" landing (a probability given the increased challenges presently associated with soft landing within a low-cost program), there needs to be sufficient programmatic support with appropriate consideration given to the required pace of technology advancement in order to appropriately prepare for future low-cost Mars mission opportunities. These technologies can be a valuable tool for astrobiological interrogation of the martian surface, providing more cost-effective, reduced risk measurements that will be complementary to larger Mars mission goals. In short, low-cost, small instruments offer a promising option to advancing our astrobiological understanding of Mars.

Related to issues of needed life detection technology is the question of planetary protection—ensuring the detection of life on Mars truly comes from martian life. Future life detection missions should collect control samples to help distinguish between biogenic and abiogenic signals and characterize the level of terrestrial contamination of martian landing sites. Though individual low-cost missions may not, themselves, be able to further conduct these more complex activities, given their limited scope and capability, it is clear that any future low-cost missions to the martian surface should ensure the highest levels of cleanliness and maintain forward planetary protection to the greatest extent possible. To that end, sterilization processes and protocols should be refined and/or adapted for low-cost missions to maintain planetary protection needs under the available cost cap. This may include new techniques or new ways to apply existing techniques for small missions.

7.3.2 Subsurface Access

Subsurface access includes remote sensing techniques to probe the subsurface and physical access techniques to get below the surface. Some of these techniques are highly amenable to a low-cost program. For remote sensing investigations, for example, groundwater sounding with transient electromagnetic sensors is under development to fit into low-cost landers to determine the presence or absence of liquid water up to several kilometers deep [Stamenković et al., 2020]. Magnetotelluric techniques (e.g., Grimm et al. [2021]) have also been proposed. A very compact ground penetrating radar is also under development as a Mars science helicopter payload, which could map layers in rock to a depth of approximately 20 meters and in ice to greater depths [Tang et al., 2022]. By flying over troughs in the north polar layered deposits, this potentially could map a few hundred meters of ice layers spanning hundreds of thousands of years of deposition [Smith et al., 2022]. Examples of these types of instruments are laid out in Appendix 6 (Table A6.1) and are recognized as having immature TRL levels for flight, potentially rectified by additional technology development.

Seismic techniques, as demonstrated by InSight, can also be used to access the subsurface without direct physical access. Detection of seismic activity can reveal tectonic, and/or possible volcanic, activity (e.g., Giardini et al. [2020]; Sita and van der Lee [2022]; Kawamura et al [2023]), from which can be obtained perspectives of the martian interior, without the need to physically access the interior. Instrument sensitivity, however, must be balanced with implementation cost. However, new approaches to seismic data collection on Mars (e.g., a global network of less-sensitive instruments) may provide opportunities to gather valuable data in an incremental fashion as individual lower-cost nodes of a seismic network are deployed at available opportunities.

Physical access techniques to get below the surface include heat flow probes like the InSight HP^3 “mole” that would need to penetrate 3 to 5 meters in soil or regolith, scoops and drills designed to access depths ranging from centimeters to kilometers, and mobility systems to access pits or lava tubes, though, naturally, not all these approaches are suitable for low-cost missions. Design considerations to overcome the difficulties experienced by the mole are discussed in Spohn et al. [2022]; investment in this might address needs of certain investigations within the Braided River. Scoops and drills to penetrate a few centimeters have already flown, and could conceivably be adapted if needed for small, low-cost landers or aerial vehicles [Perez

et al., 2016; Zacny et al. 2021]. Substantial effort has gone into development of drills for deeper access; this is less likely to fit into a low-cost mission paradigm, but low-cost mission science might help pave the way for missions with these capabilities. Surface and aerial mobility systems to access pits or lava tubes have been, and continue to be, studied [Nesnas et al., 2019; Aoki et al., 2018]; these might fit into the low-cost paradigm most readily with aerial mobility.

7.3.3 Hard Lander Instrumentation and Design

Considering a hard lander system, such as the SHIELD (Small High-Impact Energy Landing Device) concept being developed at JPL [Barba et al., 2019; Giersch et al., 2022], the instrumentation and spacecraft design will need to meet a few additional requirements beyond the general fitting of SWaP envelopes and survival throughout the mission timeline. First, the instruments must be robust against the forces engendered during landing. For example, the SHIELD design omits heatshields, parachutes, and thrusters, and uses only a basic impact attenuation system so as to keep impact forces to <2000 g; these are still much higher than the landing forces experienced by past Mars soft landings (generally <10 g, see Grover et al. [2019]).

The science mission objectives should be flexible with respect to the landing site since targeting will not be possible with an unguided entry system. Additionally, unless some post-landing mobility is included, then the orientation of the spacecraft on the ground may also not be predictable/targeted. Fortunately, there are many investigations where this is acceptable (e.g., DM investigations in Section 5.4).

If the science objective is to characterize the surface/near-surface environment, then a method for collecting measurements over a vertical profile (such as wind, temperature, volatiles/atmospheric composition) starting from the surface is needed [MEPAG, 2019]. Options include a deployable boom with several fixed sensors or a sensor that can move up/down, or a drone/balloon carrying sensors up through a higher range of elevations [Diniega et al., 2022a, b].

Accommodation of sensors away from lander influences (e.g., wind sensors on a meteorological mast or saltation sensors near the surface) would likely require careful planning but is technologically possible. More complexity arises if the measurements need to be collected during the winter season, as the thermal influence of a 'warm' spacecraft and active instrument operation may make it difficult to accurately measure the cold, local environment. A need to access the near-subsurface would also raise costs and complexity and may introduce risk if proximity to subsurface ice is required, unless a more precise landing is feasible. Similar risks may arise if specific landforms are to be imaged or accessed from relatively nearby on the surface. (Additionally, proximity to landforms potentially involving surface or subsurface ice, liquid water, or brines may raise planetary protection concerns.)

Finally, if the science objective is to characterize an actively changing environment, then potentially novel operations schemes that enable observations of sufficient frequency/fidelity will be needed to maximize science collection while staying within the power and downlink envelopes of these smaller missions. Many data science techniques have been developed that compress the amount of data that would be downlinked for science analysis, such as summarization or autonomous identification of anomalous/peak events, some of which have been implemented within prior space and planetary missions (e.g., dust devil detection on MER, or gamma ray burst detection by the Swift spacecraft) [Barthelmy et al., 2005; Chien et al., 2005;

Castano et al. 2008; Altinok et al., 2015]. These technology developments would increase the feasibility and likely science return of many of the lander-based investigations outlined in this report and broaden the relevancy of hard impact landers as a delivery platform.

7.3.4 EDL Systems

Missions targeted at the surface of Mars are among the most difficult missions NASA undertakes. Entry, descent, and landing (EDL) on Mars is challenging because there's sufficient atmosphere such that it can't be ignored, but not enough to be fully helpful in reducing entry speeds unaided. While NASA has had recent success with retro-rocket propulsion (e.g., InSight) and the Sky Crane (e.g., MSL and Mars 2020), such technologies are too expensive for the low-cost missions considered here. To date, there is no fully developed and demonstrated EDL system that would fit within the expected sub-Discovery cost cap that we expect for a low-cost class of mission ($100-300M)[9]. To this end, NASA should invest in helping to mature EDL systems for small, landed missions, following the approach laid out in the Keck Institute workshop, "Revolutionizing Access to the Martian Surface" [KISS, 2022]. These would include rough landers (e.g., SHIELD), softer landers with precision landing (e.g., that proposed for the $Mars_{DROP}$ mission concept [Williams et al., 2015]), and perhaps rotorcraft. There is currently no program to which concepts like this can be proposed for maturation, and yet they are one of the most fundamental hurdles to delivering low-cost science investigations to Mars' surface. While some advances have been maturing in the background under NASA center investments, this represents an immediate need for more NASA investment to enable the in situ science at Mars that is present across all the investigations advocated for in this report.

7.3.5 Power

Given the challenges involved in successfully with delivering a spacecraft to Mars, especially to its surface, enabling it to survive longer once there is sound economy. A main limitation for small missions is dependable spacecraft power, whether in orbit or on the martian surface. Radioisotope power systems were deemed prohibitively heavy and expensive to consider in this context. While wind or beamed energy may be options for some in situ experiments on Mars (e.g., Hartwick et al. [2023]), typically solar power is the most practical solution. In orbit, small satellites are limited in the surface area of their solar panels and solar panel area is even more limited for in situ landed spacecraft. Because of the necessity to economize on power usage, the spacecraft itself, as well as the payload, must be designed with modern computer systems to reduce the power demand of keeping the spacecraft alive and collecting observations. Additionally, investment in cold-capable electronics could reduce the heating energy needed for many spacecraft. Ultra-insulation (e.g., aerogel) could also enable delicate instrumentation to maintain comfortable working temperatures while using very little power (perhaps just self-heating). Batteries or super-capacitors that can work down to the

[9] A soft-landing EDL system also appears challenging within the Discovery cost cap. The most recent Mars soft lander—InSight—was able to fit within the Discovery cost cap with the help of contributed payload elements.

coldest expected temperatures on Mars could also broaden the feasibility of investigations by reducing the complexity and power needs to achieve them. With the recent dust-driven demises of InSight and MER Opportunity (although well after their prime mission lifetimes), we now very viscerally understand the challenges that Mars' dust presents for all missions and how it can curtail the duration of solar-powered missions. Continued study of ways to remove dust from solar panels would greatly improve the viability of these power-limited small missions as well as improve the science return of all solar-powered missions to Mars.

7.3.6 Instrument Power/Mass

The power limitations mentioned above also extend to the instruments themselves. Many high heritage instruments were built with componentry that is now outdated and thus draws far more power than more modern components would use for the same performance. For the low-cost paradigm to be successful, it is imperative that these more modern (lower power, lower mass) components be incorporated into instrument and spacecraft subsystems. To the extent that additional funding is necessary to enable this development, the MCE-SAG finds it to be a high-priority focus of the available technology budget. Apart from the gains to be had in SWaP, it also ensures these low-cost missions are not forced into limited instrument duty cycles or a reduced overall scientific payload due to overly power-hungry, outdated designs being preferentially selectable due to 'heritage'.

Similarly, EDL systems scale aggressively with spacecraft mass, so if one can reduce the landed spacecraft mass, the EDL system can be simpler and/or lighter, and thus less costly. As with power, the mass of the instruments we desire to fly on these low-cost missions should be minimized. For new instruments, the paradigm of older (read: large) instrument masses should not be accepted. For previously flown instruments that may merit re-flight, they should be re-visited to determine viable pathways to minimize their masses while not sacrificing TRL.

7.4 Risk Posture and Planetary Protection

As shown in Section 8, one of the cost drivers for space missions is risk posture. Missions are defined in terms of their risk posture as Classes A-D, where A represents the lowest risk posture in which failure would have extreme consequences to public safety or high-priority national science objectives (e.g., Mars 2020), Class B represents low risk posture (e.g., MAVEN, MRO, InSight), Class C represents moderate risk posture (e.g., Lunar Reconnaissance Orbiter), and Class D represents missions where cost/schedule are equal or greater considerations compared to mission success risks (e.g., CLPS). Risk is inherently tied to cost, as risk reduction requires additional testing during development and redundancy during design. Thus, low-cost missions are often also Class D, high-risk, missions.

The long-term viability of a low-cost Mars mission program will require acceptance of greater risk, but several approaches have been suggested that could help mitigate that risk. The "Revolutionizing Access to the Mars Surface" workshop report [KISS, 2022] promoted a strategy of "boldness," wherein maintaining frequent launches helps buy down risk long-term by enabling rapid development of technology and an experienced workforce, by decreasing the impact of any given failure, and by enabling the community to learn from challenges and failures. A program

with limited launch opportunities will be much more deeply impacted by a failure in all these ways. The report also recommends that NASA should develop a better understanding of how much risk is acceptable and who bears the risk in a low-cost program.

The Low-Cost Science Mission Concepts for Mars report [Low-Cost, 2022] specifically recommends that subsystems and parts be standardized as much as possible across missions (e.g., through bulk buys or lists of certified suppliers), while allowing more tailored approaches, where needed, to enable specific mission goals. These approaches would leverage commercial partners and the growing space economy, potentially through service-based procurement paradigms.

Both reports stress that risk assessment needs to be rethought for low-cost missions, including simplifying fault-protection approaches and testing requirements, and streamlining documentation and reporting. NASA could leverage commercial partners here as well, who have, in many cases, independently developed best practices for risk assessment that may be more appropriate for low-cost missions. However, both reports also stress that true risk reduction requires clear and well-defined communication, which should be a key component of any development strategy.

Another area of risk that is primarily relevant to landed missions are the constraints placed on Mars missions by Planetary Protection (PP). PP is the practice of limiting Earth-sourced contamination on spacecraft to protect Solar System bodies (forward PP) and protecting Earth's biosphere from spacecraft and materials returned from bodies in the Solar System (backward PP). International policies and protocols exist to provide insight into how spacecraft should be designed and assembled to meet these objectives (e.g., COSPAR [2020]; NASA [2022]).

In conjunction with the next steps for life detection is utilization of the measurement synergies between positive PP values and bioburden reduction to aid in what would be both agnostic and terrestrial biological measurements in the surface and subsurface on Mars. It is essential for future life detection missions to collect control samples as some form of "contamination knowledge" to assist future proposing scientists and science teams in distinguishing between biogenic and abiotic signals [Perl et al. 2021; Debus and Viso, 2002; Benardini et al., 2022]. Being able to leverage the needs of life detection blank standards alongside potential contamination will allow us to determine the best quality biological datasets from future martian investigations. PP also limits landing sites available on Mars based on estimates of different contamination levels, where potential "special regions" are prohibited for missions not meeting high PP standards.

7.5 Infrastructure of a Low-Cost Mars Program

7.5.1 Delivery to Mars Space

Getting to Mars is the first necessary step for small missions, whether orbital or landed. Thus, the frequency of possible rides to Mars is one control on the number of potential mission opportunities. A spacecraft can get to Mars via one of three methods: 1) rideshare (or piggyback) with a larger Mars mission, 2) rideshare to Earth orbit followed by self-propulsion, and 3) a

dedicated launch. Additionally, a suite of small missions could potentially ride together, such as being grouped on an ESPA ring. Table 3 outlines the pros and cons of each method.

Table 3*: Pros and cons of considered Mars delivery methods.*

Mars Delivery Method	Pros	Cons	Mass Available	ΔV Needed
1. Ride-along w/ Mars Mission	- Low-cost - Direct delivery	- Infrequent - Challenging integration	Low	Minimal
2. Rideshare + Propulsion	- Frequent opportunities - Flexible mission design	- Costly propulsion - Mass limited - Longer mission	Low - Med.	High (many km/s)
3. Dedicated Launch	- Full control, including schedule - More mass possible	- High-cost - Smaller launch vehicles may need kick stage	Low - High	Minimal (Mars orbit insertion only)

Ride-along with a Mars-bound primary. Sharing a ride (attached or separate) with a Mars orbiter or lander, or a flyby mission using Mars as a gravity assist to another destination. While this method may be the lowest-cost and most straightforward, suitable missions are infrequent and often come on an unreliable cadence. They also require early planning and arrangements to be in place well in advance. Co-manifesting with a primary could take the form of separation at launch (e.g., MarCO), separation prior to arrival, or delivery directly into a final orbit. In the future there may be more frequent opportunities from increasing commercial interest in Mars that could provide a ride all the way to Mars.

Rideshare to an Earth orbit and provide own propulsion. For an Earth rideshare mission, a spacecraft must have its own propulsion, cruise, and navigation capabilities. It is preferable to start from a higher-energy orbit, such as geosynchronous transfer orbit (GTO) or lunar transfer orbit (LTO) as this will greatly reduce the required Δv and trip times versus a rideshare to low-Earth orbit (LEO). Typical rideshares will make use of an ESPA ring for attachment and deployment, which carries limitations on mass and volume available (220 kg, 24x28x38" for an ESPA-class secondary payload, 465 kg, 42x46x38" for ESPA Grande-class; NASA [2021]) The total Δv from Earth orbit to Mars can be very high, which is very challenging for a small spacecraft, where much of the separated mass must be dedicated to the propulsion system and propellant.

Dedicated launch. A dedicated launch means a small mission would incur the full launch costs, but launch time, accommodations, and trajectory design would be dictated by that mission. However, typical launch vehicle costs can be prohibitively high for small missions. Thanks in part to increased competition and innovative technologies, launch costs have come down considerably in recent years. Additionally, many companies are developing a range of smaller launch vehicles with much lower costs, which, in some cases, can be comparable to the cost of

being manifested as a rideshare. Given an appropriate kick stage, these small launch vehicles could send 10’s to 100’s of kg to Mars.

Regardless of the method used to get to Mars, orbital missions must also consider how to achieve orbital insertion. Piggyback missions may have the option of riding along into orbit, where only small subsequent maneuvers would be required to reach the final orbit or landing zone. For all other missions, Mars orbit insertion (MOI) can be achieved through a direct high-thrust maneuver, a smaller maneuver plus aerobraking, spiraling down using solar electric propulsion, or aerocapture. All these methods do, however, require significant planning, hardware, and additional cost.

Rideshare missions can create many additional challenges for secondary payloads; for example, the Janus mission was slated to ride with Psyche within the SIMPLEx program, but Psyche’s launch delay led to a major mission redesign, such that Janus was no longer able to access viable targets, and it was demanifested from the Psyche launch. There also can be non-obvious incompatibility issues to be worked, driven by the needs and constraints of the primary mission, such as vibe loads during launch.

In designing a program, balancing opportunity frequency with requisite concept flexibility will be key. For example, medium-class launch vehicles could be procured by MEP on a regular cadence as dedicated carriers for small missions, avoiding launch uncertainty, integration problems, and the costs of an additional propulsion system to leave Earth orbit that come with the other launch options. Typically, the price for these types of launch vehicles is pre-negotiated to fit within budget constraints and frequency. For each launch, one or many small payloads could be accommodated, including those of commercial and international partners.

Alternatively, a program using both dedicated launches and rideshares (including potentially rideshares with the dedicated launches) is possible, increasing the number of mission opportunities while potentially keeping total launch costs lower, though this increases launch uncertainty and adds cost for integration on individual launches. If rideshare opportunities are to be included, evaluation of mission concept feasibility should include consideration of a mission concept’s flexibility; for example, how late-stage adjustments in Mars-arrival timing and location would impact achievement of the concept’s science objectives.

In all cases, the planned opportunity frequency for the program should be clearly outlined in the competition announcement. As early as possible, specific opportunities should be listed, with expected resource constraints (mass, power, size, etc.) and Mars-arrival information associated with each opportunity, so mission concept developers can tailor their concepts appropriately.

7.5.2 Telecom and Data Relay

Communicating with missions at Mars is a challenge due to the long and variable distances involved. Depending on the positions of Earth and Mars around the Sun, the range can be anywhere between 0.37 and 2.16 AU, which corresponds to about 4.3 to 21 minutes for a radio signal to propagate between the two planets. To manage this challenge, Mars orbiters typically carry a robust communications package, with large antennas and high-power transmitters. The largest system at Mars today is on MRO, which carries a 3-meter high-gain antenna in support of its science objective to perform high-resolution imaging.

Since the early 2000s, every NASA and ESA orbiter sent to Mars has also included a payload to provide proximity relay communications services to assets on the surface of Mars. These radios, by design, operate on the same frequencies (in the UHF spectrum) and with the same protocols to ensure cross-compatibility. Surface missions are enabled to carry much smaller communications packages, shifting the burden of data return from their own platforms to the Mars orbiters, which relay the data to Earth on their behalf. As of mid-2023, this “Mars Relay Network” (MRN) has returned almost 6 Tbits of data from the surface of Mars, including nearly every photograph seen from NASA surface missions since the Spirit rover landed in January 2004.

Each of the MRN orbiters have been designed as “science first” missions (e.g., Chamberlain et al. [2015]), with the relay function included as a secondary feature. Thus, the orbits and physical characteristics of the orbiters have not been designed with the provision of relay services foremost in mind. Relay services have been demonstrated by this MRN to be a critical, enabling capability for surface missions [Gladden et al. 2022], and is anticipated, by extension, to similarly enable smaller, low-cost orbiter missions as well.

Future relay orbiters could be designed to optimize the provision of relay services. Various studies (e.g., Noriega Long et al. [2023]) have been, and continue to be, performed to assess the “best” orbits for such orbiters, with the assumed use cases driving the solution sets. As the MRN ages, it becomes increasingly important to consider how to replenish or replace the current relay capabilities at Mars for future missions.

A next-generation relay architecture is expected to include new technologies to provide services to a wider variety of surface and orbital missions, considering lessons learned from today’s MRN [Gladden et al., 2018]. Such an architecture would be expected to provide services equally to large data-producing missions (such as high-resolution imagers on orbiters), to very low-power systems on the surface of Mars, and to everything in between.

It is important to note that the relay domain has four primary elements, namely: *1.* the proximity environment where relay service users communicate with the relay network orbiters, *2.* the relay network orbiters themselves, which shoulder the burden of communicating with Earth, *3.* ground tracking networks and supporting systems at Earth, which manage the distribution of relay data both to (i.e., command data) and from (i.e., telemetry and science data) the relay service user spacecraft, and *4.* the ground infrastructure necessary to manage and operate the relay network itself.

Regarding the proximity environment, a development program could be initiated to produce appropriate “terminals” for inclusion on relay service user spacecraft. Presumably, several such terminals might be worth pursuing to enable a variety of user scenarios, such as low-cost, low-power surface missions or higher-power, high-throughput orbital missions. These terminals, by design, will need to be compatible with the relay orbiters in whatever data architecture is implemented. At present, CCSDS’s Proximity-1 protocol [CCSDS 2013; 2019; 2020] is used over UHF frequencies to ensure compatibility between spacecraft at Mars, but more modern and flexible technologies and higher frequencies should be considered in next-generation relay orbiters. Key among these might be the use of delay- (or disruption-) tolerant protocols [CCSDS, 2015a, b; 2021].

Next-generation relay orbiters could be implemented with the help (or leadership) of private industry partners. As commercial entities become more capable of building spacecraft that can survive deep space environments, it becomes more feasible to rely upon such entities

for these spacecraft. Relay orbiters must have sufficient power to provide support for its communications payloads that communicate in both the proximity and direct-with-Earth directions, should be capable of providing relay services in a timely and effective manner to relay users, and carry enough onboard data storage to manage any expected data transfers, among other capabilities.

At the present time, NASA's, and ESA's Mars orbiters in the MRN use deep space ground tracking networks that are designed to support missions all around the Solar System. These tracking networks are not dedicated to communicating with missions at Mars, and therefore tracking time must be negotiated with other space missions, including those near to Earth. A next-generation relay architecture might include the use of dedicated ground antennas that are tasked principally to communicate with assets at Mars. The use of NASA's Deep Space Network (DSN) to provide direct-with-Earth communications is generally assumed when future Mars missions are considered, but this may prove to be a poor assumption.

The current MRN is considered to be a "node poor" network, where communications opportunities are sparse, and throughput is limited. As such, a ground planning and coordination infrastructure has been implemented to support the cross-project, cross-agency nature of the relay network as the operators of each mission negotiate to secure, schedule, and implement relay services. This activity is presently centralized within MEP, which acts in tandem with ESA and other organizations within NASA to match the ongoing relay needs of the Mars surface missions with the capabilities of the MRN orbiters [Wenkert et al., 2016]. MEP presently provides network-level leadership and promotes software services to enable the planning and scheduling of the MRN. Until the Mars network is no longer considered "node poor", the need for this centralized authority is expected to persist, though consideration should be given to how this may evolve in the context of other international or private industry partners.

7.6 Role of Commercial Partners

7.6.1 Role of the Space Industry in Support of Mars Exploration

The space industry plays a vital role in supporting the scientific endeavors of NASA and the scientific community. For Mars, NASA's Jet Propulsion Laboratory has managed and developed Mars orbiters and landers of a range of classes (e.g., the *Viking* 1 & 2 orbiters, *Mars Observer*, *Mars Pathfinder*, *Mars Exploration Rovers*, *Mars Science Laboratory*, and, presently, Mars Sample Return) that require significant advances in technology. Commercial companies support these activities through delivery of major subsystems, instruments, and launch vehicles (in the case of *Viking*, Martin Marietta built the landers themselves). Because significant technology development is needed for these grand endeavors, which often incur significant cost growth, NASA oversees their execution, as they may entail too much financial risk for a private company to assume.

The space industry is incentivized to optimize cost and schedule to meet requirements for mission success to satisfy the needs of the customer—typically receiving a profit, ensuring the company stays in business with balanced books, and maintaining a reputation of success for future missions. For companies, cashflow is neither directed nor subsidized, but provided only

through the competitive award of contracts or transfer of capital from other business pursuits, as is seen in some of the NewSpace companies.

Leveraging both internal technological developments, spaceflight heritage from previous missions, and government technologies released to the public, industry has been mostly successful at playing a larger role in supporting NASA's cost-capped, medium-class missions to Mars (e.g., *Mars Global Surveyor*, *Mars Polar Lander*, *Mars Climate Orbiter*, *Mars Odyssey*, *Phoenix*, MAVEN, and InSight), in addition to missions to other worlds and in support of other mission areas (Astrophyiscs, Heliophysics, and Earth Science).

In order to enact a sustainable plan for Mars exploration in parallel with the Mars Sample Return program, a well-developed business model that balances optimism and practicality through sound business acumen should be adopted that considers and incorporates viable involvement of the space industry.

7.6.2 Commercial Industry Investment for Mars: There's No Such Thing as a Free Launch.

A business model for services based upon commercial investment to support the scientific exploration of Mars is yet to be realized and likely remains outside the timeframe of this study. Commercial services at the Moon have not yet been realized, even within the "Artemis era". Practically speaking, for Earth, commercial services are only successful due to the vast number of customers, in addition to NASA, that guarantee cashflow to recuperate investment costs in a timely fashion. These customers may include the everyday needs (e.g., communication, imagery, navigation, routine launch services, etc.) of the U.S. Department of Defense, private companies, and the average citizen.

Privately funded missions for Earth have just begun to be realized to support the urgent, pressing issue of climate change. MethaneSAT, funded by MethaneSAT, LLC, will be the world's first satellite launched by an independent NGO. While similar approaches may be in formulation for planetary science, as of yet, there are no privately funded missions that have matured to implementation. Commercial investment by companies in space without guaranteed, timely cashflow have not resulted in sustainable business models on practical timescales (e.g., Deep Space Industries, Planetary Resources, Iridium).

7.6.3 Lessons Learned, Challenges, and Success from Low-cost Mission Programs.

A variety of current low-cost programs exist that can be used as analogies to examine as models for an exploration program operating in parallel with Mars Sample Return and involving industry partners. SIMPLEx, for example, is a low-cost program currently enabling planetary exploration through rideshares of small secondary payloads (<$55M). However, all five SIMPLEx missions to date have experienced significant difficulties in implementation, often due to the requirement to yield to the needs of the primary mission/launch vehicle providing the rideshare. With high risk to achieving the initially proposed mission success criteria for cost and schedule, there is little practical incentive for industry to support these missions in the future.

The Commercial Lunar Payload Services (CLPS) program, implemented at the Moon, also provides a possible model for low-cost Mars exploration. Recuring, dependable opportunities (e.g., CLPS lander contracts, PRISM-sponsored payloads, Artemis payload support, etc.) are

attractive to payload providers and vehicle vendors as a way to drive down cost and ensure resiliency of the companies. However, the recent bankruptcy of lander provider Masten Space Systems, shows that this approach is not without risk, both to NASA and its industry partners. Nonetheless, the CLPS approach seems poised to be a proven model for low-cost lunar exploration in 2023 and, despite the added challenges of getting to, and landing on, Mars, it may be a model to extrapolate for future Mars missions. To date, however, no CLPS missions have flown, and so it remains to be seen the level of success attained by this program.

Finally, the relatively low-cost Explorer program in NASA's Heliophysics and Astrophysics mission areas offers a model that has achieved great success with industry partners. A regular and reliable cadence of mission opportunities, managed by NASA, ensures that industry can offer high-heritage solutions that significantly reduce non-recurrent engineering (NRE), drives down cost, and reduces risk. NASA, in collaboration with the industry, has refined this model over decades to ensure low-cost mission success at a regular cadence of dedicated launches (See Section 7.5.1 for discussion on the benefits of dedicated launches).

7.6.4 Industry Strategies for Success.

A successful MCE program is achievable in this decade through industry partnership if practical strategies are followed. These include:

(1) Strategic alignment with the recommendations of the Decadal Survey: Coordinate industry plans, strategies, investments, and allocation of resources to support the vision of the science community.
(2) Offering competed AOs, with a range of science objectives (e.g., the Braided River): This helps guide and focus mission concepts but does not overly constrain them (as in the Astrophysics Probe and Planetary New Frontiers programs).
(3) Proper advance planning through a well-conceived Announcement of Opportunity: Well-known, familiar, tried-and-true proposal and contract structure ensures rapid initialization of a program (e.g., leveraging experience in the Earth Science MIDEX program to create a similar "MIDEX-to-Mars" process). Where feasible, a one-step proposal process could accelerate the selection and implementation of individual missions.
(4) Maintaining a reliable frequency of dedicated launches: Ensuring a regular launch cadence can energize the community through competition and enhance the process of discovery and response in a timely way. This is one of the three core elements of the Revolutionizing Access to the Mars Surface workshop report [KISS, 2022], and can help reduce cost through economies of scale for industrial partners with known, regular launch opportunities.
(5) Focusing on the challenge to reduce risk (albeit in an accepted higher-risk environment) and ensuring sustainable opportunities: The success of a low-cost program relies on dependable and regular delivery of low-cost missions to Mars. While NASA should accept a higher level of risk given the nature of a low-cost program, ensuring sustainability of a low-cost program comes from demonstrating success, learning from failure, and mitigating areas of highest risk.

(6) Leveraging larger markets: To the extent possible, a low-cost program should identify commercial markets that offer potentially usable, and exploitable, technologies for Mars exploration. An example of this is the use of the Qualcomm Snapdragon processor on the Ingenuity helicopter. The size of the mobile device industry dwarfs that of planetary exploration, and offers the potential to obtain advanced, well-validated, and well-developed components for future low-cost missions, which are not one-off, 'special order' (and, therefore, costly) products. Elsewhere, components developed for the Earth-orbiting satellite industry, which also has a market much larger than planetary, can be leveraged for use on low-cost Mars missions (KISS [2022]; Section 5.3).

8. Mission Costing

The Braided River design relies on the notion that there exist numerous mission concepts that can sustain a low-cost program over the long term. If the SAG was only able to identify a few specific missions that might be feasible over the next two decades in the $100-300M range, then such a program would have been found to be unsustainable. To address the concern that there were only limited missions that fall in this range, the MCE-SAG undertook a two-step process to first identify instrument concepts that could accomplish, in part or in whole, the specific investigations identified by the SAG. The second step was to establish rough cost estimates for the specific instrument concepts to verify which would fall under the program cost cap, and to identify the biggest cost levers that could move missions from lower into higher feasibility categories.

8.1 Inputs to Costing Exercise

As discussed in Section 4.4, the MCE-SAG drew on outside expertise to help with its costing exercise. As input, the SAG prepared a list of potential instrument designs that could address the specific investigations laid forth (as outlined in Sections 5.1-5.5). Assembling this list drew on the expertise of individual members to scour the literature and draw on personal familiarity of specific instruments and instrument concepts. A total of 83 instruments (or instrument suites, where applicable) were identified, covering each of the 28 investigations (Appendix 6). To facilitate the costing and feasibility exercise, we assembled, to the extent possible, a list of published references describing each instrument as well as best-guess estimates of its development status (i.e., TRL and/or time to TRL 6). Elements of SWaP were also obtained, along with further notes on instrument performance vis-à-vis the constraints of a low-cost mission program. This includes accommodation needs, information on data volume, heritage, and synergies with other potential payloads. Lastly, if available, an estimate of instrument cost. This latter metric relied solely on estimates of the instrument team but served as a baseline for our costing exercise.

In some cases, preliminary instrument costs suggested missions that would far exceed the cost cap of a low-cost program. (It should be highlighted that the payload makes up only a portion of the total *mission* cost, along with the spacecraft and components of other WBS elements.) In these cases, the SAG explored whether lower maturity alternatives were being developed to potentially bring down cost and increase the viability of performing similar measurements on small spacecraft. In many cases there were.

8.2 Goals of the Costing Exercise

One of the key questions behind the costing activity was to understand what could be realistically accomplished within a low-cost program of between $100-300M per opportunity. Existing programs like SIMPLEx (<$100M) and Discovery (>$500M) are well established and so the magnitude of science that can be performed in those classes has been largely characterized.

The science that can be done in the cost region between these programs had yet to be comprehensively explored.

A second key question for the SAG was, "What drives mission cost?" Specifically, for lower-cost missions, the spacecraft itself (minus payload) makes up a significant portion of an overall mission's cost. Understanding the 'pressure points' that can be alleviated to reduce cost allows us to prioritize, or elevate, those concepts that could take advantage of elements to reduce instrument cost.

8.3 Costing Model

To conduct the costing exercise, we used a JPL-developed parametric model, based on Edwards et al. [2022], to estimate spacecraft mass and cost. The model applies information gleaned from historical costing data, internal JPL studies, industry responses to JPL RFIs, and data from the JPL Team X concurrent engineering team to provide a statistical representation of spacecraft mass and cost, given user-defined inputs. Instrument costs are estimated using NICM (the NASA Institutional Cost Model), for which the basket of data driving the model is made up of flown missions, proposed missions, and estimates from commercial estimates for small-class missions to Mars. The model is applicable to orbital concepts only; a similar tool for landed mission concepts is being developed but was not available at the time of the SAG study. The discussion below, then, concerns only orbital missions in support of the program, though this does not reflect the overall science priorities of the MCE-SAG, nor should it be seen as diminishing the significance of landed missions within the low-cost program. Landed missions are seen as an essential part, especially in later stages, of a comprehensive low-cost exploration program.

As inputs to the model, the user can define: mission class (A-D), propulsion type (solar electric propulsion/SEP vs. chemical), starting and ending points (e.g., low-Earth orbit, Mars transfer orbit, low Mars orbit, etc.; see Wooley and Barba [2022]), payload type, and estimated payload mass, power, and lifetime. With this information, the tool performs a Monte Carlo of 1000 simulations, producing output that reflects, as a histogram, the overall spacecraft wet and dry mass, and payload, spacecraft, and total mission cost (including reserves). The output is not specific to any particular mission or instrument (for example, the 'payload type' input separates all possible instruments into only four general categories). It does not account for technology readiness or the particulars of an instrument's cost, nor does it include launch vehicle costs, which were out of scope of the charge of the SAG. For each instrument examined using this parametric model, we considered a mission to be 'feasible' if the median cost of the mission from the simulations was <$200M. This was to account for the high level of uncertainty carried by instrument and launch vehicle costs. Missions costing $200-300M were considered 'borderline feasible.' A list of the modeled test cases, and a demonstration of the influence of the input parameters may be found in Appendix 7.

From the assessment of the highest science priority missions (found in Appendix 5), the SAG observed that two components of mission design had the strongest influence on mission cost: (1) Mission class/risk posture and (2) Payload mass.

8.4 Cost Driver: Mission Class

Missions of the type explored here were considered to be in the range of Class C or Class D. Broadly speaking, missions of these classes are able to tolerate higher levels of technical risk, have limited lifetime (<2 years), and have a correspondingly lower cost, as discussed in Section 7.4. Model results are shown in Figure 6. To gauge the effect of mission class, the SAG prepared representative mission designs with the following characteristics and compared the predicted cost of the mission as both a Class C and Class D effort:

- 33 kg optical instrument (using a CRISM-like instrument to define SWaP)
- SEP propulsion
- Delivery from a Mars transfer orbit to low Mars orbit

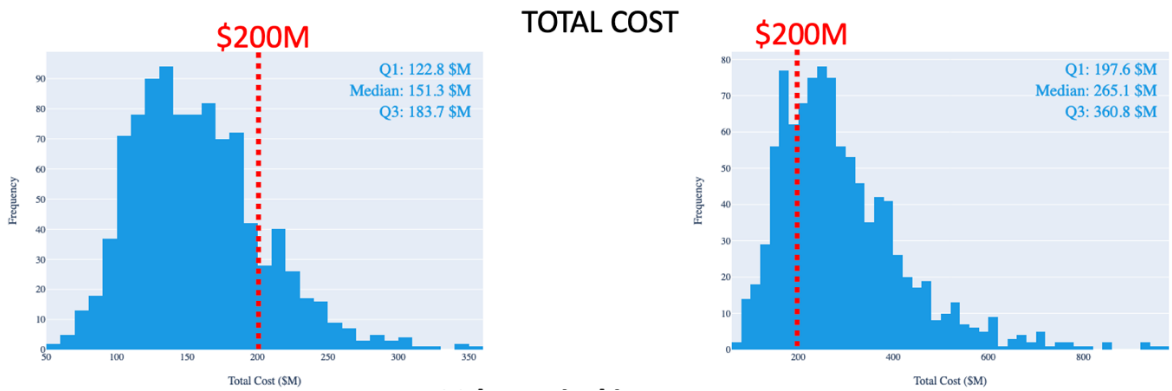

Figure 6: *Evaluation of mission cost as a function of mission class. As a Class D design (left), this sample optical mission has a median cost of $151M—well within the self-imposed $200M cost cap for a low-cost mission. Such an instrument might be a visible or IR camera or sounder, a spectrometer, or other device that measures incoming photons. As a Class C mission (right), the median mission cost increases to $265M, becoming borderline feasible, and demonstrates the cost penalty of going from Class D to Class C.*

8.5 Cost Driver: Payload Mass

The other key driver of mission cost was observed to be payload mass, where, naturally, lighter payloads result in lower mission costs. This arises from the need for a larger bus (both to accommodate the larger payload, but also to accommodate more fuel to carry the larger payload—the so-called 'wet' mass. For missions of interest, a payload mass of ~30 kg seems to be at a transition point between feasible and not. Using the same mission characteristics as above, and assuming a Class D architecture, we examined the cost of the sample ~30 kg optical instrument as compared to an instrument of approximately double the mass (65 kg, consistent with mass estimates of a HiRISE-like optical camera). The results of the costing exercise are shown below in Figure 7. Other user inputs (propulsion, start/end points) impact overall cost, but have more limited impact on overall cost (see Appendix 7 to understand the marginal effect of these inputs).

8.6 Cost Models for Specific Mission Concepts

With this general knowledge of the behavior of mission cost to the input parameters, we explored the rough cost of the orbital concepts with the highest technical feasibility from among our list of 28 investigations across the five science objectives. These concepts (and their corresponding investigations) were:

- Gravity orbiter (PE1)
- Orbital SWIR/TIR Spectroscopy (PE2; EE1)
- Climate Orbiter/Upper Atmosphere Orbiter (multiple variations) (DM2; DM4)
- Orbital Sounding Radar (RC1)

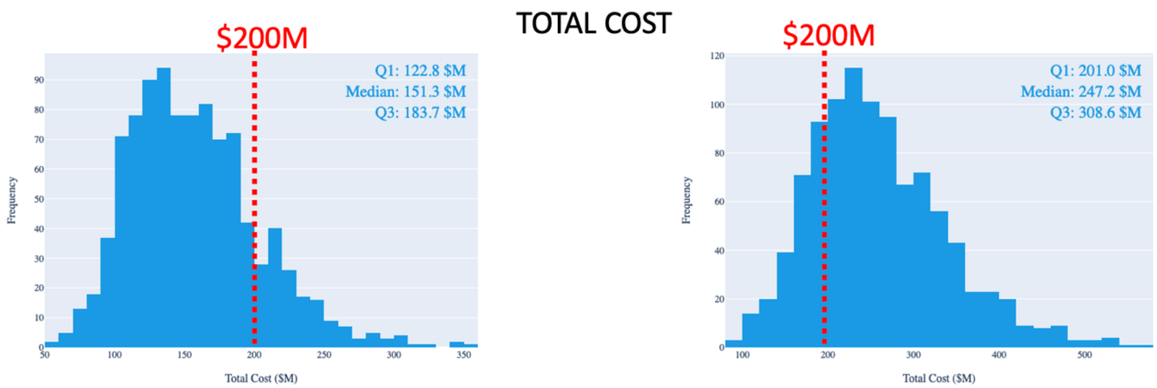

Figure 7: *A doubling of instrument mass from 33 kg (left) to 65 kg (right) increases the cost of the feasible, $151M (median) payload to $247M, and into the 'borderline' category.*

Gravity Orbiter: The concept includes either microwave or laser ranging in a spacecraft-to-spacecraft tracking architecture, similar to the instruments flown or tested on GRAIL, GRACE, and GRACE-FO, thus having high TRL. A Class D gravity orbiter mission, using SEP to arrive at low Mars orbit from a Mars transfer orbit, had a median cost of $126M, and was considered to be feasible from a cost perspective.

Orbital SWIR/TIR Spectroscopy: A range of options exist in this investigation space, and this mission concept includes both multispectral and hyperspectral spectrometers in the visible and near-infrared wavelengths, derived from THEMIS, CRISM and HiRISE. These instruments have high heritage, but a range of TRL levels that likely require additional development. A Class D orbital spectroscopy mission, using SEP to arrive at low Mars orbit from a Mars transfer orbit, had a median cost of $151M, and was considered to be feasible from a cost perspective. Other instruments of similar SWaP are also likely feasible.

Climate Orbiter/Upper Atmosphere Orbiter: Climate monitoring payloads are generally low mass and volume, and thus permit a range of permutations to 'mix and match' instruments depending on the desired data to be obtained. We examined several options building off a basic, baseline payload of a weather camera (derived from the MRO MARCI camera). With the same constraints as above (Class D, SEP), such a basic climate orbiter had a median cost of $47M. Alone, this permits a range of other spacecraft options to be considered (chem propulsion, delivery from low-Earth orbit, etc.). An enhanced payload instrument suite, adding a UV imager and IR sounder (both flight-tested and high TRL) brings the median cost to $105M. Addition of a LIDAR

instrument brings the median cost to $212M, placing it in the 'borderline feasible' status. Other instruments, similar in SWaP to the LIDAR (e.g., a sub-mm sounder, Doppler wind sounder), generally lead to similar borderline costs.

Orbital Sounding Radar: While desirable to conduct high-priority science, the cost of an orbital sounding radar was found to exceed the cost cap of a low-cost program, even as a stand-alone instrument. Assuming the same constraints as above and drawing on examples from the literature and examples already fabricated, the median cost of a radar was estimated at $378M. More complex radar systems than those explored here might be several times even more expensive. Thus, it was acknowledged that, at present, an orbital sounding radar was likely not feasible for the program, although future advancements in technology might help to reduce the cost to the point where it could be considered.

9. Summary

The past 50 years of Mars exploration have shown that Mars is a dynamic and habitable world with a unique record of planetary processes through time, and MSR would provide major leaps forward in many scientific and technological areas. However, future exploration concurrent with, and beyond, MSR could address many important questions regarding the dynamism of martian geophysics, geology, climate, and astrobiology of Mars that fall outside the scope of the Mars Sample Return program.

Based on the MCE-SAG's evaluation of the current state of robotic exploration technology, expected future developments, and the major outstanding scientific questions at Mars, we find that a new low-cost mission program could make significant scientific progress at Mars. The most exciting scientific questions that can be addressed uniquely at Mars using low-cost missions all fall under our central theme -- ***Dynamic Mars****: Investigating ancient and modern drivers of change on an active planet.* The Dynamic Mars program would use orbital and landed missions to explore preserved records of the past, investigate modern, active processes, and prepare for future exploration by larger robotic or crewed missions.

The MCE-SAG identified 28 different investigations that could be addressed within the Dynamic Mars program, grouped under five scientific objectives: Planetary Evolution, Early Environmental Change, Recent Climate Evolution, Dynamic Modern Environments, and Modern Habitability. Based on a detailed assessment of the maturity and capabilities of available instruments and by applying preliminary costing models, we find that at least seven of these investigations could be addressed under a low-cost program ($100-300M) using orbital missions leveraging existing technology, and thus could be solicited now to fly within the next few years. A further 12 investigations could be addressed in the near future with additional technology development, particularly in areas that would enable deployment of simple landed missions such as through development of "hard lander" EDL systems and/or high-g tolerant instruments. More advanced technologies, like soft landings, subsurface access, aerial platforms, and surface mobility, will likely need significant additional development before they could be implemented as part of a low-cost program. Such developments would take place in latter stages of a low-cost program.

We envision the Dynamic Mars program as a competed program that would solicit missions to address any of the Dynamic Mars scientific objectives, but without prescribing a specific technical approach for those missions. This principle of openness maximizes innovation and impact by allowing NASA to identify the most compelling and feasible missions that could conduct the highest priority science. Further, this flexibility would allow the program to make progress on multiple objectives at once as scientific understanding evolves. We envision the Dynamic Mars program as having a ***"Braided River" architecture:*** an *interconnected network of low-cost missions working together to address major outstanding Mars questions*. This architecture recognizes that most big Mars questions cannot be fully answered with a single instrument, but that multiple small missions working together over time can make substantial progress.

A low-cost mission program like Dynamic Mars has wide ranging benefits. In addition to addressing high-priority science questions, such a program would enable development of new

technology with wide applications and promote integration of the commercial sector into Mars exploration. It increases opportunities for competition and expands the roster of mission leadership to include scientists, and institutions, that might be overlooked in a more traditional mission program. However, for such a program to be successful and paradigm changing, it would need to be well supported by frequent solicitations, regular launches, and robust technology development programs. It is the opinion of the MCE-SAG that this new approach would be highly complementary to the existing Mars Exploration Program mission portfolio and inject the excitement and novelty of a decidedly new approach to exploring the Red Planet.

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Appendix 1: Charter

Mars Concurrent Exploration (MCE)-SAG Charter
Mars Exploration Program Analysis Group (MEPAG)

Purpose

The Mars Sample Return (MSR) program represents the execution of the consensus highest priority science goal for the Mars science community as noted in the *Visions and Voyages* Decadal Survey (DS), and reaffirmed by the present Decadal Survey, *Origins, Worlds, and Life (OWL)*. However, as noted in *Visions and Voyages* and outlined in *OWL* and in the MEPAG Goals, while MSR will be a major step forward, the Mars Exploration Program (MEP) has additional important priorities that cannot be addressed by MSR alone. Major new science questions have emerged in the last decade beyond MSR, as revealed in recent findings from the Mars Architecture Strategy Working Group (MASWG), the Ice and Climate Evolution Science Analysis Group (ICE-SAG), the *OWL* report, the Low-Cost Science Mission Concepts for Mars Exploration Workshop, MEPAG's recent update to the MEPAG Goals document, as well as community input through MEPAG meetings over the last three years. These fundamental questions can be broadly categorized as: diversity of ancient habitable environments, Amazonian climate change, the Martian ice budget over time, and the dynamic nature of present-day Mars. Recognition of this breadth of new, and addressable, science questions at Mars is seen in *OWL* through the recommendation that NASA should maintain the MEP to develop and implement a comprehensive exploration architecture concurrently with the MSR program. *OWL* also affirmed that low-cost exploration can be part of the MEP strategy to advance scientific and human exploration goals.

The Mars Concurrent Exploration Science Analysis Group (MCE-SAG) is tasked to collate and synthesize a broad range of inputs to express community consensus on the highest priority science that should be executed in parallel with MSR, with a focus on those that can be addressed under a low-cost mission model (e.g., budget classes between and including SIMPLEx and Discovery). The ultimate goal is to develop a program architecture to begin regularly flying competed low-cost Mars missions addressing high-priority science within the next ten years.

The SAG will focus on low-cost missions, as these will constitute the backbone of the MEP during the MSR era. The SAG will leave to future SAGs the task to further develop mid-level missions discussed in *OWL*, including the I-MIM mission, which is currently under study by a dedicated Measurement Definition Team, and the Mars Life Explorer mission concept, which requires further focused study. However, the SAG may consider how these missions or mission types could integrate into and be supported by a low-cost mission program.

Statement of Task

With this charter, the MEPAG Steering Committee forms the MCE-SAG to identify and prioritize scientific objectives and/or investigations that could be executed within the next ten years, in parallel with the MSR effort and in conjunction with *OWL* guidance for the Mars Exploration Program (MEP). The MCE-SAG shall:

- Identify high-priority science objectives that could be achieved in parallel with MSR to address fundamental planetary science questions traceable to the MEPAG goals document and the *OWL*, as well as recent SAG report findings and recommendations.
- Assay these objectives to identify constituent parts that are executable as standalone investigations that contribute to a broader program of Mars science; and
- Determine how such investigations might be addressed within a low-cost mission program (Discovery budget class and smaller missions) within the next decade.
- Determine what technology development and Mars infrastructure will be needed to support these low-cost Mars missions.

Approach

The SAG shall take into account the following:

- The current MEPAG Goals document as well as recent high-impact results from all fields of Mars science that may not be fully incorporated in the 2020 version of that document.
- The report of the Mars Architecture Strategy Working Group (MASWG) dated November 2020.
- The KISS workshop report on Revolutionizing Access to the Martian Surface (Culbert et al., 2022).
- The report of the Ice and Climate Evolution Science Analysis Group (ICE-SAG), with consideration for the possibility that the International Mars Ice Mapper (I-MIM), with or without additional science activities presented by the I-MIM MDT, may address some ICE-SAG findings.
- The report of the Low-Cost Science Mission Concepts for Mars Exploration Workshop held in March.
- Recent direction by the *OWL* discussing recommendations for Mars exploration activities aside from MSR-related ones.
- Official findings, community contributions, and discussion outputs from MEPAG virtual and face-to-face meetings that are pertinent to this charter.
- The SAG is also empowered to request from the community any other pertinent information necessary to complete their tasks.

Methods

- The MCE-SAG will consist of 2 Chairs and ~15-20 members selected from the Mars Community.
- In an effort to broaden participation within the Mars community, this selection will be an open call and an evaluative rubric has been designed for the Steering Committee to evaluate the applicants in an equitable way.
- SAG Member Selection
    - The MEPAG SC will announce an open call for self-nomination to the MCE-SAG
    - Applicants will be asked to provide their CV of no more than 2 pages and a Cover letter of no more than 2 pages to the SC. The cover letter should include:

        - A discussion of the nominee's knowledge and expertise as they match one or more areas of expertise listed in the call, and how these would contribute to the goals of the MCE-SAG
        - A discussion of their mission experience, including active missions, mission proposals, and mission concept exercises.
        - A discussion of any large-scale program experience and or budgeting experience
        - A discussion of their understanding and support of MEPAG and the MEPAG community
        - A description of availability for SAG meetings and tasks as noted in the call
    - The individual members of the MEPAG SC will use selection rubric to evaluate the qualifications of each candidate and how they align with SAG needs.
    - Each member of the SC will then rank the candidates and submit their ranking to the selection coordinator (the past Chair of MEPAG).
    - The selection coordinator will collate the rankings and provide them to the SC; the SC will discuss the candidates and select 15-20 to be members of the MCE-SAG.
- The MCE-SAG will be formed and begin its deliberations following the MEPAG 39 meeting.
- The MCE-SAG will conduct its business primarily via telecons, e-mail, and/or web-based processes. If circumstances permit, a face-to-face meeting may be accommodated, if needed.
- When added expertise is needed, the MCE-SAG will request a briefing from recognized subject matter experts.
- The Lunar and Planetary Institute (LPI) will provide logistical support.

Schedule and Deliverables

- A preliminary report (in ppt format) is requested to be presented to the Steering Committee by 1 August 2022.
- A draft report will be reviewed by the MEPAG Steering Committee and, if approved, will be presented for input from the MEPAG community at a subsequent MEPAG meeting.
- A final report is requested by 15 September 2022.
    - The report must not contain any material that is ITAR-sensitive.
    - The SAG members may opt to have their report reviewed externally.

Appendix 2: MCE-SAG Community Announcement

To the Mars Community,

The Mars Exploration Program Analysis Group (MEPAG) has chartered the Mars Concurrent Exploration Science Analysis Group (*MCE-SAG*) to identify and prioritize scientific objectives and/or investigations that could be executed within the next ten years, in parallel with the Mars Sample Return effort, and in conjunction with Decadal Survey guidance for the Mars Exploration Program (MEP). The *MCE-SAG* charter is attached to this call, and will shortly be found on the MEPAG website at *www.lpi.usra.edu/mepag*. Further details about the purpose, scope, approach, and deliverables of the SAG may be found in the attached charter.

To maximize the value of the SAG's final report, MEPAG is seeking representation across a broad range of scientific and technical fields, including, but not limited to:

- Astrobiology
- Atmospheric Science
- Geology
- Geophysics
- Planetary Protection
- Technology (incl. mobility systems, subsurface access, life detection, communications, mission operations)

Self-nominations for participation on *MCE-SAG* are being solicited through June 5, 2022, with selections occurring soon thereafter. The anticipated period of SAG activities will be late June-late September 2022. Because of the short timeline, applicants should anticipate a regular, weekly meeting cadence during this period, with meetings done chiefly by WebEx, and communications by email.

Applicants are asked to submit their CV of no more than two pages, and a cover letter of no more than two pages (as a single, combined document), indicating interest in *MCE-SAG* participation, and touching upon those evaluation elements listed in the *MCE-SAG* Charter under 'Methods/SAG Member Selection'. As MEPAG is seeking a balance of experiences and expertise, selection to the SAG does not require knowledge of, or experience in, all evaluation elements. Applicants from all career levels are encouraged to apply.

Appendix 3: The MCE-SAG Members

FIRST NAME	LAST NAME	AFFILIATION
Michael	Mischna	*JPL* (co-chair)
Briony	Horgan	*Purdue* (co-chair)
Don	Banfield	*NASA Ames*
Claire	Newman	*Aeolis Research*
David	Kass	*JPL*
Alejandro	Cardesín Moinelo	*ESA/ESAC*
Brian	Jackson	*Boise State*
Jennifer	Heldmann	*NASA Ames*
Mary Beth	Wilhelm	*NASA Ames*
Scott	Perl	*JPL*
Heather	Graham	*NASA GSFC*
Mike	Sori	*Purdue*
Dave	Brain	*CU Boulder-LASP*
Robert	Citron	*UC Davis*
Michael	Phillips	*JHUAPL*
Serina	Diniega	*JPL*
Edwin	Kite	*U. Chicago*
Solmaz	Adeli	*DLR*
Richard	Volpe	*JPL*
Michael	Veto	*Ball Aerospace*
Moogega	Cooper	*JPL*
Aditya	Khuller	*ASU*
Jon	Bapst	*JPL-MEPO*

Appendix 4: The MCE-SAG Activity Timeline

Activity	**Date (all 2022)**
Establishment of Charter	April 18
Community Announcement Released	May 27
Application Deadline	June 5
Application Review	June 9-15
Membership Selection	June 17
Member Notification	June 17
Introductory Meetings	June 27, 29
Weekly Meetings	July 6, 11, 20, 25 August 3, 8
Mid-Term Summary Presentation Delivery (to MEPAG leadership & MEP)	August 12
Weekly Meetings	August 22, 31 September 7, 14, 19, 28
Final Summary Presentation Delivery (to MEPAG leadership & MEP)	October 24
Presentation to MEPAG	October 27
Final Report (this document) Delivery	TBD

Appendix 5: Science objectives and investigations

	Investigation	Science Priority	Feasibility	Supporting documents
Planetary Evolution (PE): *Characterize the geodynamic, petrologic, thermal, and tectonic evolution of the crust and interior of Mars from the Pre-Noachian through the present day.*				
PE1	Determine the global structure of the martian crust and lithosphere, including the origin and nature of the hemispheric dichotomy	High	High	OWL 4.3, 5.1, 5.2, 5.3, 5.6; MEPAG Goal III A, B
PE2	Determine the composition and petrologic evolution of the early martian crust	Medium	High	OWL 5.1, 5.2; MEPAG Goal III B1, B2
PE3	Characterize Mars' ongoing volcanotectonic activity	High/Medium	Medium	OWL 5.1, 5.2, 10.6; MEPAG Goal III B1.2
PE4	Characterize the geophysical properties and geological evolution of the Mars dichotomy boundary	High/Medium	Low	OWL 5.1, 5.2; MEPAG Goal III B
PE5	Constrain the history of the martian core dynamo	Medium	Low	OWL 5.1, 5.2; MEPAG Goal III B2
PE6	Quantify the impact bombardment history at Mars	Low	Low	OWL 4.2, 4.3; MEPAG Goals II C1 and III A4
Early Environmental Change (EE): *Understand the processes that drove habitability and climate change on early Mars as recorded in the ancient stratigraphic record.*				
EE1	Characterize the nature and timing of ancient aqueous deposits and major environmental transitions on early Mars	High	High	OWL 5.4; MEPAG Goal A1, A2, A3; NEX-SAG Findings 13, 16
EE2	Determine the controls on early habitability on Mars	High	Medium/ Low	OWL 10.1, 10.2; MEPAG Goals I A2 and III A1, A2, A3
EE3	Determine the nature, distribution, preservation, and sources of organic matter on ancient Mars	High/Medium	Medium/ Low	OWL 9.3, 10.4, 11.1; MEPAG Goal I A1, A2, A3, B1, B2
EE4	Constrain the earliest stages of Mars atmosphere evolution	Low	Low	OWL 3.6, 6.1, 6.2; MEPAG Goal II C1
Recent Climate Evolution (RC): *Understand modern volatile transport and the drivers of recent climate change using global ice records and atmospheric reservoirs.*				
RC1	Determine how Mars' climate has changed over orbital time scales as recorded in global ice stratigraphies	Medium	High	OWL 5.4, 6.2; MEPAG Goals II A2, B1, B2, B3, and III A1; NEX-SAG Findings 4, 5; ICE-SAG Findings 2, 5; I-MIM Finding 5
RC2	Constrain recent climate change on Mars	High	Medium	OWL 5.4, 6.2, 6.4; MEPAG Goals II A, B and IV C; ICE-SAG Finding 2
RC3	Determine the age of martian ice deposits	High	Low	OWL 5.4, 6.2; MEPAG Goal II A, B; NEX-SAG Finding 15; ICE-SAG Findings 2, 4

RC4	Determine the presence or absence of near-surface liquid water within ice deposits on Mars.	Medium	Medium	OWL 6.2, 6.4, 10.3; MEPAG Goals I A and II A, B; ICE-SAG Finding 7; I-MIM Findings 3, 4, 5
RC5	Determine the relationship of layers in ice stratigraphies to climate and atmospheric processes by characterizing seasonal volatile fluxes.	Medium	Low	OWL 6.2, 6.4; MEPAG Goal II A2; NEX-SAG Finding 3; ICE-SAG Findings 2, 5, 6
RC6	Determine seasonal and annual ice transport rates on Mars.	Low	High	OWL 5.6, 6.4; MEPAG Goal II A, B; ICE-SAG Finding 6
Modern Habitability (MH): *Understand how recent climate on Mars has affected the habitability of the near-surface and subsurface to support the search for present-day life.*				
MH1	Search for currently habitable deep subsurface environments on Mars	High	Medium	OWL 10.1, 10.2; MEPAG Goals I A2 and III A1
MH2	Search for evidence of present-day life near Mars' surface	High	Low	OWL 11.2, 11.3; MEPAG Goal I A1
MH3	Constrain the source location and origins of potentially biogenic gases	Medium	Medium	OWL 11.1, 11.2; MEPAG Goals I B1, II A3, and III A4
MH4	Search for currently habitable shallow subsurface environments on Mars	Medium	Medium	OWL 10.1, 10.2; MEPAG Goals II A2, B2, III A1, and IV C2; ICE-SAG Finding 8; I-MIM Finding 5
Dynamic Modern Environments (DM): *Understand processes controlling for modern surface and atmospheric environments on Mars by characterizing meteorology, atmospheric fluxes, and other dynamic processes*				
DM1	Understand the surface drivers of the dust and water cycles on Mars, including dust storms	High	Medium	OWL 6.3, 6.4, 6.6; MEPAG Goals II A1, A2, III A2, and IV B1, B2, B4; NEX-SAG Finding 6; ICE-SAG Finding 3
DM2	Understand atmosphere/climate variability including the timing of dust storms	High	High	OWL 6.3; MEPAG Goals II A1, A2, and IV A1, B3; Terrae Novae Weather Network
DM3	Understand the present-day water and CO_2 exchange between the atmosphere and subsurface	High/Medium	Low	OWL 6.4; MEPAG Goals I B1, II A2, and IV A3; NEX-SAG Finding 10; ICE-SAG Finding 3, 6; I-MIM Finding 5
DM4	Determine how lower atmospheric dynamics influence atmospheric escape to space	Medium	High	OWL 6.5; MEPAG Goals II A4, and IV A1
DM5	Determine the location, rate, and nature of episodic, seasonal, and interannual surface changes at high spatio-temporal resolution	Medium	Medium	OWL 6.4; MEPAG Goals II A1, A2, and III A1, A2

DM6	Characterize the current systems in the martian ionosphere and magnetosphere	Low	Medium	OWL 6.5; MEPAG Goals II A4, and IV B4; I-MIM Finding 6
DM7	Determine the rate and mechanism of modification of polar or aeolian landforms at high spatio-temporal resolution	Low	Medium	OWL 6.4; MEPAG Goals II A2, and III A1, A2; NEX-SAG Finding 8
DM8	Understand and characterize the controlling factors for surface weather on Mars	High/Medium	Medium	OWL 6.3; MEPAG Goals II A1, A2, A4, and IV A1, B3; Terrae Novae Weather Network; NEX-SAG Findings 9, 12; ICE-SAG Finding 3

Appendix 6: Instrument concepts

The table below provides detail on the 74 instrument concepts considered by the MCE-SAG to conduct the science investigations formulated by the SAG to address the five top-level science objectives. It is not prepared as a comprehensive list—other instrument concepts may exist to perform similar investigations, and their absence should not be seen as a lack of SAG endorsement. For each instrument concept (row) information on the specific investigation(s) that it addresses is provided, along with basic descriptive information about the instrument, its capabilities and/or limitations, and the provider (if known). References in the literature to the instrument or method are provided, along with a best effort estimate of technology readiness (drawn either from the literature or personal familiarity among the SAG membership). Elements of SWaP and cost, if know or published, are also included. From among these instruments were drawn payloads that could address the highest priority science investigations (Table 2). A similar activity may be conducted for lower priority investigations as the low-cost program evolves.

While the costing tool, itself, makes a determination on overall mission cost, this can be adjusted accordingly, if it is known a priori, for example, that an instrument is particularly expensive, due either to complexity or needed technology development.

Table A6.1: List of instruments considered during the costing exercise, along with capabilities, references and size, weight, power, and cost estimates. Items in this table are not prioritized.

Investigation Reference	Instrument type	Contributor of Instrument (if known)	Key capabilities/requirements	Instrument concept(s) - references if possible	Development status - TRL if possible, time to TRL 6	Mass	Cost	Other notes (accomodation, data volume, etc.)
GP1, AE1	Gravity (microwave ranging system, spacecraft-spacecraft tracking)	JPL	spacecraft ranging measurement of 6 x 10^-7 m/Hz^0.5 (GRAIL)	https://link.springer.com/chapter/10.1007/978-1-4614-9584-0_4	TRL 9 (flown on GRAIL, GRACE, and GRACE-FO)	TBD	TBD	There are other ways to collect gravity data, but I just picked 3 so as not to take over too many rows (for example, there's the radio tracking of single spacecraft, but that's already been done at Mars and we need something more for non-minor improvement)
GP1, AE1	Gravity (laser ranging interferometry, spacecraft-spacecraft tracking)	JPL, Max Planck Institute	spacecraft ranging measurement of 8 x 10^-8 m/Hz^0.5 (GRACE-FO)	https://iopscience.iop.org/article/10.1088/1742-6596/610/1/012010	TRL 8 (tech demo on GRACE-FO)	TBD	TBD	
GP1, AE1	Gravity (atom interferometer gradiometer)	TBD	TBD	https://www.science.org/doi/full/10.1126/science.1135459?casa_token=lujwLz02AvYAAAAA%3A9bF9ZF4h2StoPvUVaZRAmUAj7fYzwOwp4h1LGJEyyhOXiRj5QbhpxCIMZGg432ayM1_Ve-RKmv_VVQs	my guess is TRL 4, but not sure	TBD	TBD	
GP5, AE1, IR1	Orbital Thermal IR multispectral spectrometer	ASU	6.0-100 µm (1666-100 cm−1) with a spectral sampling of 5 cm−1	https://link.springer.com/article/10.1007/s11214-018-0513-6	TRL 9 (flown on MGS, Lucy, Osiris-Rex, and EMIM)	6- 16 kg	$15M	
GP5, AE1, IR1	Orbital VNIR/SWIR multispectral spectrometer	APL	<10 m/pixel resolution (preferred ~1-2 m/pix) (C-IMG: 1 m/pixel)	https://ui.adsabs.harvard.edu/abs/2012LPICo1683.1047M/abstract MORIE PMCS (C-IMG) https://iopscience.iop.org/article/10.3847/PSJ/abe4db	Unk.	~19 kg	TBD	Something like LORRI could be adapted for multispectral imaging
GP5, AE1, IR1	Orbital VNIR/SWIR hyperspectral spectrometer	APL	<20 m/pixel resolution (preferred: CTX resolution, 5-6 m/pixel) (MISE: 25 m/pixel at 100 km range) (NGSWIS: <5 m/pixel) (HVM3:)	MISE on Europa Clipper: https://trs.jpl.nasa.gov/bitstream/handle/2014/54997/CL%2321-2096.pdf?sequence=1 MORIE PMCS (NGSWIS) https://iopscience.iop.org/article/10.3847/PSJ/abe4db Trailblazer HVM3	CRISM: TRL 9 (flew on MRO, capable of 18 m/pixel)	(CRISM: 32.92 kg)	~$130M (from Murchie/Seelos)	A CRISM 2.0 would likely be a joint JPL/APL effort. Lower mass and volume are achievable in 2022 than was possible in 2002 due to advances in optics and sensor technology.
IR1	Orbital Thermal IR Imager	ASU APL	(25 m/pixel; 6-50 µm for next THEMIS) <100 m/pixel for Mars-FIRE/tTIRS/LTM	E-THEMIS on Europa Clipper: https://trs.jpl.nasa.gov/bitstream/handle/2014/54997/CL%2321-2096.pdf?sequence=1 MORIE PMCS (Mars-FIRE) https://iopscience.iop.org/article/10.3847/PSJ/abe4db PREFIRE TIRS https://ieeexplore.ieee.org/abstract/document/9843559 Trailblazer LTM	THEMIS/E-THEMIS: TRL 9 (flown on Mars Odyssey and will fly on Europa Clipper)	~12 kg	$22M (for next THEMIS)	
IR1	Orbital sounding radar	ISA/JPL	~ 100 MHz for top 10 m that SHARAD can't 'see'	N/A	Relatively high TRL	TBD	TBD	I-MIM anchor payload is ~930 MHz, so much higher frequency than here. Want to look to deeper depths. MORIE radar is ~400 MHz.
GP3	Orbital SAR	JPL	10-100 MHz; should be capable of polarization and nadir-sounding to detect subsurface ice	N/A	Unk.	TBD	TBD	
GP3	Orbital InSAR	JPL	Capability of detecting seasonal and longer-term change of surface volatiles, surface displacement from seismic or tectonic activity	https://meetingorganizer.copernicus.org/EPSC2020/EPSC2020-513.html?pdf	TRL 9	TBD	TBD	
MH1	Transient electromagnetic loop	JPL+SwRI	Detect saline aquifer at >5 km depth	https://ui.adsabs.harvard.edu/abs/2022LPICo2655.5054N/abstract https://www.hou.usra.edu/meetings/lowcostmars2022/pdf/5054.pdf	TRL 4 achieved as of 2022	< 10 kg, <= 30 W	"Low"	Per Chad Edwards and Larry Matthies (orally on 9/7/22): 100m diameter antenna. Mass and power consistent with low-cost (e.g. rough) lander. During FY19-FY21 JPL funded development: Vlada Stamenkovic was JPL lead, then Nunes took over after Stamenkovic moved to Blue Origin.
MH1	Deep-sounding landed radar	Centre d'Etude des Environnements Terrestre et Planétaires/IPSL, Saint-Maur, France	Detect saline aquifer at >5 km depth	https://ui.adsabs.harvard.edu/abs/2003JGRE..108.8027B/abstract and https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2002JE001867 - importantly, coherent addition due to fixed lander and fixed target allows very many orders of magnitude better S/N than for an orbiting radar	Unclear (European). TRL 5 ?	~500 g according to Ney et al. 2003 https://ieeexplore.ieee.org/document/1350463	Unknown, but total development cost for Netlander is "less than 100 M Euros" according to Dehand et al P&SS 2004 https://www.sciencedirect.com/science/article/pii/S003206330400087X	

Investigation Reference	Instrument type	Contributor of Instrument (if known)	Key capabilities/requirements	Instrument concept(s) - references if possible	Development status - TRL if possible, time to TRL 6	Mass	Cost	Other notes (accomodation, data volume, etc.)
IR2	Ground-penetrating radar (shallow)	JPL	Ability to resolve fine layering in upper 10's meters of layered ice deposits	https://www.hou.usra.edu/meetings/lowcostmars2022/pdf/5066.pdf	Unk.	mass of approximately 0.9 kg and radar power of 2.5 W	TBD	Per https://www.hou.usra.edu/meetings/lowcostmars2022/pdf/5066.pdf , "A new technology GPR instrument is under development at JPL that will meet the requirements of the helicopter designed for operation in the NPLD regions. This miniature GPR is expected to have mass of approximately 0.9 kg and radar power of 2.5 W. With 900 MHz of bandwidth, the instrument will provide resolution of better than 20 cm to the depths of 25 m and lower resolution deeper."
GP6	Geochronology	SwRI (CDEX) GSFC (KArLE) U. Maryland (ICPMS) JPL (UCIS)	Precision better than 5% for rocks 4.5 Ga (~200 Myr), desired to be 1% (per 2015 NASA Technology Roadmap)	https://iopscience.iop.org/article/10.3847/PSJ/abedbf	All TRL 6 except ICPMS (TRL 4)	CDEX ~80 kg KArLE ~30 kg ICPMS ~12 kg UCIS ~6.5 kg	TBD	
IR4	Microwave radar (landed) for liquid water within snow/ice, snow stratigraphy and thickness	COTS parts - would require rad-hardened versions	Detect subsurface liquid water within ice/snow ; frequency-modulated continuous wave (FMCW) radar (25-40 GHz)	In-situ prototype version: https://www.cambridge.org/core/journals/journal-of-glaciology/article/subsurface-melting-in-a-seasonal-snow-cover/6891788317E79BB7F1BBE08D66AE9DF6#R14 Airborne-version: https://espo.nasa.gov/impacts/instrument/FMCW Similar COTS version: https://www.ti.com/lit/ds/symlink/awr1843.pdf?ts=1664132830304&ref_url=https%253A%252F%252Fwww.google.com%252F	TRL 6	< ~1 kg	"Low"	Galin, N., A. Worby, R. Massom, G. Brooker, C. Leuschen, P. Gogineni, and P. Jansen (2008), 2-8 GHz FMCW radar for estimating snow depth on Antarctic sea ice, 2008 International Conference on Radar, 2-5 Sept 2008, 276-281. https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.498.5307&rep=rep1&type=pdf
IR4	Dielectric probe (landed)	JPL	Measuring water with depth using electrical spectroscopy	https://www.hou.usra.edu/meetings/lpsc2020/pdf/3015.pdf	TRL 6	TBD	TBD	
GP3	Subsurface heat probe	DLR	Surface heat flow with uncertainty better than +/- 5 mW/m2 (as per InSight)	InSight HP3 https://link.springer.com/article/10.1007/s11214-018-0531-4?utm_source=getftr&utm_medium=getftr&utm_campaign=getftr_pilot	TRL 9	~3 kg	$10's M	
GP3	In situ heat flow probe	Honeybee	In situ subsurface temperature measurements, capabilities do rely on dwell times, ref. VIPER mission.	https://www.hou.usra.edu/meetings/lpsc2021/pdf/2400.pdf	~TRL 6 (to fly on VIPER mission, late 2023)	low	TBD	
GP2	In situ gravimeter (mobile or network?)	TBD	TBD	MEMS gravimeter paper: https://www.nature.com/articles/nature17397 https://www.science.org/doi/10.1126/science.aat0738?siteid=sci&keytype=ref&ijkey=xakdRhWj7CWEE	Using IMU accelerometers has been demonstrated with MSL, so TRL 9	0.75 kg (LN-200S IMU from NGC)	Potentially low, or 'free' if IMU is necessary component on s/c	
GP2	In situ magnetometer (mobile or network?)	UCLA	Insight Fluxgate Magnetometer. See also VIPER Vector Magnetometer Lander	https://an.rsl.wustl.edu/help/Content/About%20the%20mission/INS/Instruments/APSS.htm	TRL 9 (flown on Insight)	< 500 g	low	
GP3	Seismic network	JPL, CNES	Detection of local and/or shallow quakes	Ruggedized SP seismometers for soft/hard landers, penetrators. can you get the sensitivity you need for a regional application? Not as applicable for global distribution https://www.hou.usra.edu/meetings/lowcostmars2022/pdf/5024.pdf (penetrators)		O(10) kg each element	TBD	
AE2	In situ remote geochemistry	Many portable versions are COTS, JPL (SHERLOC, but see note about resolution)	Vibrational spectroscopy (typically 532 nm which is sensitive to most chemistries), LIBS	N/A	SHERLOC already in flight but needs to be micro-Raman (i.e., attached to a microscope) for microtextures (see below in organic detector justification)	TBD	TBD	

Table A6.1 (cont'd)

Investigation Reference	Instrument type	Contributor of Instrument (if known)	Key capabilities/requirements	Instrument concept(s) - references if possible	Development status - TRL if possible, time to TRL 6	Mass	Cost	Other notes (accomodation, data volume, etc.)
AE2,AE3,AE5	In situ remote mineralogy	Many portable versions are COTS, JPL (SHERLOC, but see note about resolution)	Vibrational spectroscopy (typically 532 nm which is sensitive to most mineral suites), VNIR and IR spectroscoscopy (IR for crystalline structures), spatial resolution to show distribution in grains/outcrop, camera (microscope preferred)	N/A	SHERLOC already in flight but needs to be micro-Raman (i.e., attached to a microscope) for microtextures (see below in organic detector justification)	TBD	TBD	
AE2,AE3,AE5	In-situ mineralogy (VNIR+TIR) + particle size/thermal inertia/temperature	ASU	VNIR: 1-2.5 µm TIR: 5-50 µm (10 cm-1, i.e., 4 nm @ 2 µm spectral resolution) Spatial Resolution: 0.5/2 cm spot in NIR/TIR at 3 m	Based on Mini-TES (TRL 9); proposed to M2020 https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2003JE002117	TRL 6	4.5 kg	$8-16M	Selectable NIR or TIR hyperspectral radiance acquired every 2 seconds when operating.
AE2,AE3,AE5	In situ remote mineralogy, volatile detection	Ames: NIRVSS (Near Infrared Volatiles Spectrometer System)	Point NIR spectrometer: 1300-4000 nm Broad band tungsten lamp for NIR illumination of spectrometer FOV 4 MP CMOS imager, with seven color LEDs (348, 410, 540, 640, 740, 905, and 940 nm) for color imaging; at a working distance of 30 cm the spatial resolution is ~100 µm Four-channel thermal radiometer	Manifested on VIPER, multiple CLPS flights https://ntrs.nasa.gov/api/citations/20210000168/downloads/20210000168%20-%20Roush%20NIRVSS%20LPSC%202021%20abstract%20submitted.pdf	TRL 6. Flying on Peregrine Mission 1 to the Moon, so TRL will be even higher (if successful)	3.5 kg	<<$50M (total PRISM cost cap for entire instrument suite)	total power is about 18 W (spectrometer, camera and radiometer), not including the tungsten lamp (which is 12 W). Each sensor system/illumination-source can be operated simultaneously or individually.
AE6	In situ geochronology	SwRI (CDEX) GSFC (KArLE) U. Maryland (ICPMS) JPL (UCIS)	TBD	https://iopscience.iop.org/article/10.3847/PSJ/abedbf	All TRL 6 except ICPMS (TRL 4)	CDEX ~80 kg KArLE ~30 kg ICPMS ~12 kg UCIS ~6.5 kg	TBD	
IR2, IR4, IR5	In situ subsurface ice mapping (H)	Ames: NSS (Neutron Spectrometer System)	Detection of water/hydrogen in subsurface down to ~1 m	Manifested on VIPER, multiple CLPS flights	TRL 6+ (draws on Lunar Prospector NSS heritage). Flying on Peregrine Mission 1 previously, so TRL will be even higher (if successful)	pretty small (PRISM mass cap is 50 kg for entire suite)	<<$50M (total PRISM cost cap for entire instrument suite)	
CP1, CP8	Meteorology station (p, T, surface wind, Absolute Humidity, etc.)							
CP1, CP8	Pressure	FMI, COTS	Range: 0-12 mb, precision: 0.1 Pa, accuracy: 1 Pa	MEMS COTS devices likely feasible, "coffee can" devices also work, but are huge and power hungry	TRL 5	50g for MEMS, 1kg for "coffee cans"	low	
CP1, CP8	Temperature	CAB, JPL, Ames, etc.	Low radiative cross-section (visible and IR)	thin-wire thermocouple	TRL 9	20g	low	
CP1, CP8	Winds	Ames, CAB	Depends on science case, but note that high-frequency 3D is **required** for flux measurements (e.g., to get u* and hence wind stress for aeolian studies; sensible heat flux; water or trace gas fluxes, etc.)	Sonic is best and something like this is **required** for high-frequency 3D. hot wire/film may be OK for some cases. Microphones might also suffice	TRL 5	500 g	$7 M	0.5W. Accommodation should be on a dedicated met mast, or at least such that there are not lander elements close to the anemometer that disturb the wind flow either thermally or mechanically.
CP1, CP8	Absolute Humidity (please not RH)	SWRI, JPL	Near-surface (within few m altitude) water concentration: 1 ppm res; 20 Hz when expect exchange (overnight/coldest times + sunrise), one minute average every hour otherwise	TLS is best. RH fails to resolve right when science gets interesting	TRL 5	300 g? 1 kg if TLS	$6 M for TLS with two channels from Rafkin/SwRI	
CP1, CP8	Atmospheric gas constant/density	SWRI	CO_2 concentration, 2x per day	TLS: CO_2 channel A multi-channel tunable laser spectrometer for in situ measurement of planetary atmospheres: https://ieeexplore.ieee.org/abstract/document/7119065	TRL 5	1 kg	$6 M for TLS with two channels from Rafkin/SwRI	TLS can be compatible with the sonic anemometer
CP1	Upward/downward radiative spectrometers	CAB, Ames	Net downwelling & upwelling radiation i [DS(1] n visible & IR: 0-7000 W/m^2; ≤1 W/m^2; 2.5 Hz sampling	CAB has M2020 sensors, Ames has VIPER sensors	TRL 9	~1 kg	relatively low	
CP1	Aeolian instrumentation (sand flux, e-field, imager)							

Table A6.1 (cont'd)

Investigation Reference	Instrument type	Contributor of Instrument (if known)	Key capabilities/requirements	Instrument concept(s) - references if possible	Development status - TRL if possible, time to TRL 6	Mass	Cost	Other notes (accomodation, data volume, etc.)
CP1	Saltation Sensor	Ames	[DS(1]I think this would also fit here, especially since we're looking at heat flux … I'm not clear fully yet what a radiometer does so am not sure what the right Physical Parameter or Observable would be.	Banfield's Saltation Sensor PICASSO	TRL 4	TBD	TBD	
CP1	e-field sensor		TBD	Schiaparelli http://www-mars.lmd.jussieu.fr/granada2017/abstracts/montmessin_granada2017.pdf	TRL 6	TBD	TBD	
CP7	Change-detection/context imaging - surroundings	JPL	Imaging to track changes in surface albedo (reflecting e.g., grain cover) and small landforms (e.g., nearby impact ripples), imaging frequency of hourly during periods of high activity out to weekly when few changes are occuring	InSIght IDC	TRL 9	0.25 kg each	TBD	
CP7	Change-detection/context imaging - near-field (i.e., grains on ground)		Imaging able to resolve individual grains (~100 microns or larger) on the ground	MAHLI	TRL 9	2.5 kg (incl. electronics)	TBD	
CP7	Also need to measure u* and air density to get wind stress		Vertical wind profile (from ≥2 altitudes, 0.5-1.5 m) and Temperature measurements: at ≥2 altitudes (0.1-1.5 m); 10-20 Hz; 150-300 K range, +/- ≤1 K	MEDA/REMS p,T sensors for density	TRL 9	<1 kg	TBD	
CP1, CP3, CP8	Trace gas sensor	SWRI, JPL	Species identification, fast response preferred, low power, low mass; ideally coupled with 3D high-freq wind sensor for flux measurements	Tunable Laser Spectrometer	TRL 6 (TRL 4-5 for some species)	400 g (depends on species)	$6-15 M (depends on provider and species)	Scot Rafkin (SWRI) and Chris Webster (JPL). Ideally couple with a 3D high-freq anemometer for measuring not only abundances but also fluxes of different species.
CP2, CP4, CP5	Weather camera	MSSS	Diurnal global coverage	MARCI on MRO	TRL 9 (in flight)	835 g (481 g for the camera)	$6M (per MOSAIC proposal)	There are many other proposed designs for this role
CP4	Orbital UV imager	France, CU-LASP	Examine the upper atmosphere	MEx/SPICAM, MAVEN/IUVS or EMM/EMUS	TRL 9 (in flight)	9 kg (SPICAM), 27 kg (IUVS), 18 kg (EMUS)	$30 M (IUVS)	28 W (IUVS) 15 W (EMUS)
CP2, CP4	IR Sounder	JPL	Profiles of temperature, dust, water ice and water vapor from surface to ~80 km, surface observations of temperature	MCS on MRO and Diviner on LRO	TRL 9 (in flight)	9 kg	$25 M	2 kbps, 18 W
CP2, CP4	Advanced IR Sounder	JPL	Profiles of temperature (2.5 km vertical resolution), dust, water ice and water vapor from surface to ~80 km, surface observations of temperature	AMCS (MOSAIC Study)	TRL 9 (minor differences from MCS)	9 kg	$25 M	4 kbps, 18 W
CP2, CP4	Mini IR Sounder	JPL	Profiles of temperature (2.5 km vertical resolution), dust, water ice and water vapor from surface to ~80 km, surface observations of temperature	Mini MCS (MOSAIC Study)	TRL 6	3.5 kg	$10 M first, $5 each afterwards	4 kbps, ~ 2U in size, 8 W
CP2	Orbital Wind LIDAR	GSFC	Profiles of wind (near surface & lower atmosphere < 50 km), temperature, pressure & density, aerosol opacity	MARLI (MOSAIC Study)	TRL 6(?)	38 kg	$40 M	50 kbps, 81 W
CP2	Orbital sub-mm limb sounder	JPL	Profiles of wind (lower & middle atmosphere surface to ~100 km), water vapor and temperature	MOSAIC Study (two antenna version)	TRL 5 (TRL 6 with $50 K & 3 to 6 months)	35 kg	$35 M	10 kbps, 50 W
CP2	Orbital mini sub-mm sounder	JPL	Profiles of wind (lower & middle atmosphere surface to ~100 km), water vapor and temperature	MOSAIC Study (one fixed antenna version)	TRL 5 (TRL 6 with $50 K & 3 to 6 months)	11.5 kg	$25 M	5 kbps(?), 15.6 W
CP6	Orbital vector e-field	TBD	TBD	N/A	Unk.	TBD	TBD	
CP2	Mars Doppler Wind and Temperature Sounder (MDWTS)	Ames	MDWTS utilizes gas cell radiometers to measure winds with an accuracy of better than 5 m/s day and night from the near surface (<5 km) to altitudes as high as 120 km with < 5 km vertical resolution.	Aeolus mission concept, led by A. Colaprete - AGU 2021 abstract https://ui.adsabs.harvard.edu/abs/2021AGUFM.P15B2098C/abstract	TRL 4 (planned TRL 5 by 2024)	Total launch mass 40.8 kg (as of 2017)	TBD	Aeolus was one of two Martian smallsat concepts selected for study through the Planetary Science Deep Space SmallSat Studies program. Aeolus would consist of a single satellite in a near-polar orbit, allowing it to pass over all local times, with the baseline mission observing all seasons of an entire Martian year (two Earth years). The lowest cost approach has Aeolus as a ride-along that used the prime spacecraft for
CP2, CP4	Thermal Limb Sounder	Ames	Will measure atmospheric temperatures, water ice clouds, and dust abundances across all altitudes where winds are measured.		High TRL (TES etc. heritage, see row 5)			

Table A6.1 (cont'd)

Investigation Reference	Instrument type	Contributor of Instrument (if known)	Key capabilities/requirements	Instrument concept(s) - references if possible	Development status - TRL if possible, time to TRL 6	Mass	Cost	Other notes (accomodation, data volume, etc.)
CP2	Surface Radiometric Sensor Package	Ames	SuRSeP is a nadir viewing radiometer, will measure the total reflected solar and emitted thermal radiance, surface temperature, and water cloud and dust total column abundances.		TRL 6 (as of 2018)			orbit insertion and relay communication through other existing orbiting assets. Volume: 45 x 35 x 52 cm; Total power 46.1 W; Data Throughput (UHF DL): 1Mbps (as of 2017)
CP2	Mini TIR Spectrometer (for atm. temp., dust and water profiles)	ASU	TIR: 5-50 µm (10 cm-1, i.e., 4 nm @ 2 µm spectral resolution)	Based on Mini-TES (TRL 9); proposed to M2020 https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2003JE002117	TRL 9	~2.5 kg	< $8 M	
MH2	Meter-class drill	JPL	Impactor vs. Drill vs. Mole requires a different capabilities wrt what sample removal type we want. More on this TBD..	Mars Deep Drill (MDD) concept. Plan is for impactor depths of 100m.	TRL 2 (as of last week), intent is for TRL 4-5 or higher by FY25	TBD	TBD	
MH2	Meter-class drill	Honeybee Robotics	1 m rotary percussive drill, capable of bringing cuttings to surface (10 cm "bites") for measurement, also developing embedded instrumentation in drill string for in situ measurements down borehole (neutron spec, NIR spec, thermal probe, dielectric spectroscopy, etc).	https://www.hou.usra.edu/meetings/lpsc2021/pdf/2400.pdf	TRIDENT drill, selected for lunar flight missions (VIPER, PRIME-1)	drill mass = 20 kg without harness; avionics mass = 5.4 kg	TBD	
MH2	Organics detector/life detection characterization payload	Many portable versions are COTS, JPL (SHERLOC, but see note about resolution)	Vibrational spectroscopy (typically 532 nm which is sensitive to most mineral suites), spatial resolution to show distribution in micron-scale grains, microscope	N/A	Unk.	TBD	TBD	
MH2	SOLID (Signs of Life Detector)	CAB	Detect whole cells, complex organic molecules, and simple polymers of possible biogenic origin	https://www.sciencedirect.com/science/article/pii/S0032063305000280 https://www.liebertpub.com/doi/full/10.1089/ast.2010.0501 https://www.liebertpub.com/doi/10.1089/ast.2007.0217	Unk.	TBD	TBD	
MH1	Magnetotellurics	TBD	TBD	N/A	Unk.	TBD	TBD	
GP2, GP5	Rotocraft deployment	JPL	Ingenuity+ development for MSR should be able to carry a few 100 g payload (e.g., magnetometry, gravimetry, imaging)	https://arxiv.org/abs/2010.06630 Delaune et al, IEEE Aerospace Conference 2022, Mid-Air Helicopter Delivery at Mars Using a Jetpack https://arxiv.org/abs/2203.03704	To be tried on Dragonfly. TRL for Mars is ~3/4?	N/A	Hard to get rotocraft down to <$300 M without ridealong options	
GP5, AE1, IR1	Ralph - visible multiband imager/IR spectrometer	Ball	75 mm aperture, 0.66 m focal length MVIC: iFoV= 19.77 µrad, FOV width 5.7 degrees, 32 TDI lines, Blue/Red/NIR/methane bands LEISA: iFoV=60.8 µrad, FoV 0.9 x 0.9 degrees, 1.25 - 2.5 µm bandpass with	Reuter et al. 2008	9	10.5	TBD	
AE1,CP5	HiRISE - high resolution visible multiband imager	Ball	0.5 m aperture, iFoV=1 urad, 128 TDI lines, Bands Red/Blue/NIR	McEwen et al. 2007	9	65	TBD	
AE1,CP5	Deep Impact HRI - visible narrow angle camera/IR spectrometer	Ball	30 cm aperture, 10.5 m focal length w/ beamsplitter Visible: iFoV = 2 µrad, FoV = 0.118 degrees IR: iFoV = 10 µrad, bandpass 1.05 - 4.8 µm, R>216	Hampton et al. 2005	9	53	TBD	
CP2	Calipso Wide Field Camera - visible wide angle camera	Ball	iFoV = 177 µrad, FoV = 5.2 deg	Weimer et al. 2004	9	2.6	TBD	
AE1,GP5	L-CIRiS - multiband thermal imager	Ball	iFoV = 2 mrad Bands 7.7 - 8.1 µm, 8.0-8.4 µm, 8.3 - 8.9 µm, 7.5 - 13.5 µm	Osterman et al. 2020	6 (launch in 2025)	9	TBD	
CP2	Revelio high dynamic range visible multiband wide angle camera	Ball	iFoV = 186 µrad, FoV = 23 x 27 degrees 8 bands possible, read noise < 2 e-, full well = 30,000 e-	https://ui.adsabs.harvard.edu/abs/2020AGUFMP084...02S/abstract	4 (2.5 years to TRL 6)	2	TBD	
MH1,AE3	UV imager	MSSS, JPL	TBD	WATSON, MAHLI	In-flight	few kg	TBD	
CP2	Miniaturized VIS Wide Angle Camera	AAC	4 MP imager, > 30 MP/s scan rate 16 mm F1.2 or 25, 35, 50 mm F2.0 lens	IM200 https://www.aac-clyde.space/what-we-do/space-products-components/payloads/im200	TRL ~6? (flown on Earth Orbit)	<100g	TBD	Example of COTS for low resolution global climate monitoring onboard smallsats

Table A6.1 (cont'd)

Investigation Reference	Instrument type	Contributor of Instrument (if known)	Key capabilities/requirements	Instrument concept(s) - references if possible	Development status - TRL if possible, time to TRL 6	Mass	Cost	Other notes (accomodation, data volume, etc.)
CP2	Miniaturized VIS Wide Angle Camera	INTA	450 to 650 nm, 12.16×9.25 deg FOV, 640×480 pixels	APIS OPTOS https://doi.org/10.1117/1.JRS.13.032502	TRL ~6? (flown on Earth Orbit)	120g	TBD	Example of COTS for low resolution global climate monitoring onboard smallsats
	Compact VIS/IR Camera	IACTEC	1.1 and 1.6 µm	DRAGO https://www.iac.es/en/projects/iactec-space	TRL ~6? (flown on Earth Orbit)	1kg	TBD	Example of COTS for low resolution global climate monitoring onboard smallsats
AE1,AE2,AE3, AE5	Compact IR Spectrometer	THOTH	1.2-2.2 µm range, 6 nm spectral sampling, 0.15º iFOV	ARGUS 2000	TRL ~6? (flown on Earth Orbit)	500g	TBD	Example of COTS for low resolution global climate monitoring onboard smallsats
GP5,AE1	Compact Thermal InfraRed Mapper	VTT	6-25 µm	TIRI/MIRMIS	(in dev for Comet Interceptor)	4.5kg	TBD	Other heritage: VIRTIS/Rosetta/Venus Express, MERTIS/BepiColombo, MAJIS/JUICE, MCS/MRO, Diviner/LRO; CMS/TechDemoSat-1; LTM/LunarTrailblazer, ...
CP6	Compact Ion Analyzer	Tokai Univ.	3D velocity distribution of low-energy ions (from 5 eV to 30 keV)	Mercury Ion Analyzer	TRL ~6? (flown on Mercury)	~1kg	TBD	
CP6	Compact Solar Wind Monitor	IRF	low energy neutral atom (10 eV-3.3 keV) and an ion mass spectrometer (10 eV-15 keV)	SARA/Chandrayaan-1	TRL ~6? (flown on Moon)	~1kg	TBD	
GP2, GP4, CP6	Miniaturized Magnetometer	INTA	AMR sensors for medium- to high-sensitivity (~3 mV/V/G) and resolution (~30 µG)	METEO/AMR	TRL ~6? (flown on Earth Orbit)	500g	TBD	Simple example of COTS for low resolution global climate monitoring onboard smallsats

Table A6.1 (cont'd)

Appendix 7: Costing model details

A series of costing runs was performed using a JPL parametric costing tool to explore the viability of a range of orbital mission concepts to conduct the highest priority science as laid out in the MCE-SAG report above. The tool provides a range of input parameters to define the payload. These are listed here in Table A7.1, along with a description of the options used and their impact on mission cost:

Mission Class: Class-C or Class-D. Class-D is a higher risk class which lowers the overall cost of the mission due to elimination of many redundancies and acceptance of lower assurance standards.

Propulsion Type: Solar Electric Propulsion (SEP) or Chemical (Chem). Chemical propulsion is more costly and heavier, but affords a more direct, quicker, transit to Mars. SEP reduces cost and mass, but requires a lengthier, more circuitous, route to Mars.

Start/End Point: The location from which the spacecraft will begin and end its trajectory. Options explored are low-Earth orbit (LEO), Mars transfer orbit (MTO), areostationary orbit (Areo), and low-Mars orbit (LMO). In general, LMO is the preferred destination orbit for payloads to accomplish the highest priority science. Start and end point dictates how the spacecraft will get to Mars, and may require a carrier vehicle (i.e., as a hosted or secondary payload) or fuel tank to get to the final orbit.

Payload Type: Defined in the model as 'Optical', 'Fields', 'Active Microwave' and 'Passive Microwave'. All proposed instruments are placed into one of these categories. The Optical classification includes instruments which detect and process UV/visible/IR radiation (e.g., cameras, spectrometers). The Fields classification includes instruments detecting fields (e.g., magnetic, or gravitational). The Active Microwave category covers active radar instruments, while the Passive Microwave category covers sensors that passively detect microwave or sub-mm wavelengths. Multiple instruments may be included on a single payload and can vary across categories.

Payload Mass/Power: Estimates of instrument mass and power consumption. Where such values are unknown (especially power needs), we assume a 1 W/kg ratio.

Payload Design Life: How long is the mission designed to last? Assumed to be 36 months unless otherwise noted.

Output values include mass and cost, covering both the payload and total mission. Mission total costs that fall within the $200M cost cap (reserving $100M for uncertainties not captured by the model) are colored in green in the 'Mean Total Cost' column. Others are colored in red. Outputs of interest are listed below:

Mean Dry Mass: Mass of the spacecraft (incl. payload) exclusive of fuel
Mean Wet Mass: Mass of the spacecraft (incl. payload) with fuel included
Mean PL Cost: Estimated cost of the instrument payload, alone
Mean SC Cost: Estimated cost of the spacecraft bus, exclusive of payload
Mean Total Cost: Estimated cost of the mission, Phases A-F

Optical Instruments of Various Types

Instrument	Mission Class	Propulsion Type	Start Point	End Point	Payload Type	Payload Mass (Likely)	Payload Power (Likely)	Payload Design Life (Likely)	Mean Dry Mass	Mean Wet Mass	Mean PL Cost	Mean SC Cost	Mean Total Cost
CRISM-like	D	SEP	MTO	LMO	Optical	33	33	36	401	554	17.3	42.4	145.4
	D	Chem	MTO	LMO	Optical	33	33	36	592	1917	17.2	51	165.9
	C	SEP	MTO	LMO	Optical	33	33	36	401	550	17.5	128.2	268.2
	C	Chem	MTO	LMO	Optical	33	33	36	587	1897	17.2	170.8	340.5
	This shows that a lot of cost savings come from doing SEP vs. chem, and class D vs class C. Payload is an optical instrument like a CRISM spectrometer												
	D	SEP	LEO	LMO	Optical	33	33	36	917	2089	17	64.4	199.4
	About a $50M hit to go from LEO instead of MTO.												
	D	SEP	LEO	LMO	Optical	33	33	24	947	2167	15.2	64.5	191.7
	Reducing lifetime from 3 years to 2 years (though ~half of this would be getting to Mars). Negligible change in mission cost.												
HiRISE-like	D	SEP	LEO	LMO	Optical	65	160	36	1493	3432	48.6	80.6	318
	These are the parameters for HiRISE 2.0, which falls out of scope if coming from LEO												
	D	SEP	MTO	LMO	Optical	65	160	36	620	855	50.6	51.9	251.5
	Same as the previous, but now coming from MTO. Something like HiRISE could be done for low-cost program, but barely, and with Class D rating. Couldn't fly two to mitigate risk.												
	C	SEP	MTO	LMO	Optical	65	160	36	624	862	50.1	165.4	394.6
	A Class-C mission of this type would exceed the cost limits of a low-cost program												
Weather Camera	D	SEP	MTO	LMO	Optical	2	2	36	73	101	1.2	18.8	48
	A small, Class-D weather camera would fit well within the cost constraints												
	D	SEP	LEO	LMO	Optical	2	2	36	159	369	1.2	27.4	68.4
	Even from LEO, such a payload is quite viable												
	D	Chem	MTO	LMO	Optical	2	2	36	193	625	1.2	29.4	72.9
	Chem is OK for these light payloads, though about a 50% price increase.												

Table A7.1: Results of the costing exercise for the highest priority science investigations, demonstrating those concepts which are feasible in a low-cost program (green text in 'Mean Total Cost' column) and those which are borderline or not feasible (red text). Acronyms/abbreviations are as listed in the Appendix 7 text.

Gravity Orbiter	D	SEP	LEO	LMO	Fields	20	20	36	680	1551	15.1	54.5	169.1
	This represents a 20 kg instrument for a gravity orbiter. Payload estimated to be in the $15-20M ballpark. Quite doable from LEO												
	D	SEP	MTO	LMO	Fields	20	20	36	288	396	15.2	35.3	124.3
	Even better from MTO (about 20% cheaper).												
	D	SEP	Areo	LMO	Fields	20	20	36	193	225	14.9	28.2	106.5
	Delivery to areostationary orbit saves another 10%												
Radar	D	SEP	MTO	LMO	Active Microwave	20	20	36	284	394	24.7	36.1	151.5
	Changing to an active microwave, the instrument is substantially more expensive, but still viable. Mission is ~20% more expensive than a Fields experiment												
	D	SEP	LEO	LMO	Active Microwave	20	20	36	679	1554	24.4	56.8	199.2
	Going from LEO instead makes it more expensive, but still viable.												
	D	SEP	LEO	LMO	Active Microwave	100	100	36	1885	4333	100.3	90	473.6
	Consider a heavier radar (~100 kg). This quickly becomes too costly.												
	D	SEP	Areo	LMO	Active Microwave	100	100	36	527	610	93.9	45.8	346
	Even bringing it to areostationary orbit, it's still too costly.												
Climate Suites	D	SEP	LEO	LMO	3x Optical	15	20	36	569	1307	10.6	50.6	147.2
	Multi-instrument payload (Weather Camera, UV Imager and IR Sounder, using estimates from MCE-SAG Spreadsheet												
	D	SEP	Areo	LMO	3x Optical	15	20	36	158	186	10.5	26.3	88.4
	Delivery to areostationary orbit reduces cost even further. Very viable concept												
	D	SEP	LEO	LMO	4x Optical	53	101	36	1300	2981	39.4	76.7	281.9
	Adding a MARLI-like LIDAR to the payload makes it particularly challenging.												
	D	SEP	LEO	LMO	3x Optical + 1 passive microwave	50	70	36	1226	2811	55.9	75.7	317.8
	Swap out MARLI lidar for a sub-mm limb sounder (treated here as a passive microwave instrument). This increases cost even further.												

Other Payloads

Table A7.1 (cont'd)