National Aeronautics and Space Administration

Expanding the Horizons of Mars Science

A Plan for a Sustainable Science Program at Mars

MARS EXPLORATION PROGRAM

2024-2044

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ACKNOWLEDGMENTS

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ABOUT THE PLAN

Background

NASA's Mars Exploration Program (MEP) is a science-driven, robotic-focused effort to characterize and understand Mars, including its current environment, climate and geological history, and biological potential, and to prepare for human exploration. Over the past two decades, MEP has made numerous scientific and technical breakthroughs by building on the entire history of Mars exploration to create and maintain a series of robotic missions, including orbiters, landers, rovers, and helicopter.

Scope

The Plan provides guidance and priorities for the next 20 years (2024–2044) of MEP's science and robotic efforts and its role in achieving the nation's ambitions at Mars. It is designed to be in alignment with the NASA Strategic Plan (2022) and the NASA Science Mission Directorate (SMD) Science Strategy (2023 version); NASA's Moon to Mars Strategy and Objectives Development (2023); the current Planetary and Astrobiology Decadal Survey (Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023–2032) (2023); the Mars Exploration Program Plan (last approved in 2021); and multiple Mars science community reports. The MEP 2024–2044 Plan provides a strategic approach for a sustainable scientific program at Mars. While this plan is complementary to and supportive of NASA's Moon to Mars Strategy and Objectives Development (2023), it does not define or alter any aspects of NASA's human exploration program.

Motivation

This plan was developed in response to near-simultaneous findings in the Planetary and Astrobiology Decadal Survey (2023) and the NASA MEP Program Implementation Review (2021). These findings (see the following page of this report) both recommend MEP develop a comprehensive plan to consider missions, infrastructure, technology, and partnerships.

EXPANDING THE HORIZONS OF MARS SCIENCE:

A Plan for a Sustainable Science Program at Mars

“NASA should maintain the Mars Exploration Program, managed within the PSD [Planetary Science Division], that is focused on the scientific exploration of Mars. The program should develop and execute a comprehensive architecture of missions, partnerships, and technology development to enable continued scientific discovery at Mars.”

– OWL (2023)

“A Program strategy should be developed … following the release of the Decadal Survey. The strategy should provide a clear plan of action that includes the overarching science goal for the decade, mission cadence, opportunities for a mix of small, medium, and large missions that increase opportunities for competition and broad community participation including the commercial sector, and that includes a strategy to replenish the communication infrastructure.”

– MEP Program Implementation Review (2021),
Standing Review Board Recommendation

INPUTS TO THE PLAN

REPORT / ACTIVITY	PARTIAL LIST OF TOPICS ADDRESSED
OWL (2023): Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023–2032	Mars Sample Return (MSR), Mars Life Explorer, International Mars Ice Mapper (I-MIM), human exploration, research & analysis, technology, infrastructure, state of the profession
MEPAG (2020): MEPAG Science Goals, Objectives, Investigations, and Priorities, 2020 Version	Mars-science-community consensus on scientific priorities as recommendations for MEP mission planning
MASWG (2020): Mars Architecture Strategy Working Group **MCE-SAG (2023)**: Mars Concurrent Exploration Science Analysis Group	Strategies for addressing major outstanding Mars questions such as mission arcs (MASWG); interconnected networks of competed, lower-cost missions (MCE-SAG); dynamic Mars; imaging needs; mission classes
KISS RAMS (2022): Keck Institute for Space Studies (KISS) Revolutionizing Access to the Mars Surface	Sustainable architecture to reduce landed Mars costs through efficient operations of multiple assets, leveraging lunar capabilities, and partnerships
LCSMC (2022): Low-Cost Science Mission Concepts for Mars Exploration Workshop	Viability of small missions, mission concepts, industry partnering
MEPIND: Mars Exploration Program Industry Day & subsequent interactions	Partnerships to enable access to Mars, including spacecraft / lower-cost mission delivery systems and payload hosting, telecom relay, imaging, and weather monitoring
I-MIM MDT (2022): International Mars Ice Mapper Measurement Definition Team	Ice science / ice record, reconnaissance, meeting the need for high-res imaging, relay
M2M (2023): NASA Moon to Mars Strategy and Objectives Development	International and commercial collaboration (RT-1/2), commerce & space development (RT-9), volatiles/core samples of frozen volatiles (LPS-3/SE-3), life (LPS-4), resources (AS-3), astronaut science training (SE-1), planetwide robotic research (SE-6), planetary protection (SE-7), etc.
NM: NASA Models	Incorporation of lessons learned from other NASA programs (e.g., COTS/CLPS)

For reading ease, these community inputs will be referred to by the bolded abbreviations as listed in the table above, with full citations at the end of this document. See also Appendix C for a summary of specific alignments.

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PREFACE

Mars is a very special place. Fascination with the Red Planet goes back as early as astronomers in ancient Egypt. The Babylonians and the Greeks tracked the motion of the planet. Galileo made the first telescope observations of Mars. Even today, when we look into the night sky to see a pale red dot above us, it inspires us to wonder about this nearby world that has some similarities to Earth, and yet is so drastically different.

NASA has spent the past five decades sending orbiters, landers, rovers, and even a helicopter to explore our mysterious neighbor. Nothing quite captures the imagination of the world like landing on Mars after passing through the “seven minutes of terror.” What was once thought to be a barren wasteland has proven to be a destination of great wonder. At one time in the past, Mars was likely abundant with water and potentially had life. What happened on Mars that it diverged so dramatically from our home planet of Earth? This is a fundamental question that can help unlock the mysteries of our solar system.

Throughout the course of human history, exploration of our planet has changed our world through discovery. Similarly, the great robotic Mars explorers of our time—among them, Mars Reconnaissance Orbiter and Mars rovers *Curiosity* and *Perseverance*—are radically changing our understanding of Mars, allowing the world to come along and participate in their voyages of discovery. As with our exploration of Earth, the more we learn about Mars, the hungrier we become for more knowledge. Yes, we have had amazing successes at the Red Planet, but there remains so much more to explore. The reality is that we have only explored a small fraction of Mars, and the places yet to be explored are among the most interesting: the Martian subsurface, caves and lava tubes, and nearly all of the polar regions…just to name a few.

Human exploration of Mars is an inevitability, but before the first boot steps on Mars, there is so much work to be done. We must continue our search for life on Mars…be it ancient or present. We must better characterize locations with sources of water, as a key resource for future astronauts. We must also understand the planet’s dynamics, related to climate, geology, and atmosphere.

As successful as NASA has been in our exploration of Mars, the future is dependent on collaboration. Space agencies around the world and commercial entities in the space sector have never been more capable or expressed more interest in Mars than we are seeing today. Great achievements at Mars will be enabled by increased international collaboration and partnering with industry.

In addition, we must challenge conventional thinking and look to new and creative solutions for the exploration of Mars. This can include seeking lower-cost science investigations, strengthening our infrastructure around Mars, seeking new enabling technologies, and creating an environment that broadens participation in Mars exploration.

The achievements of the past and present have been amazing. But it is now time to turn the page and write the next chapter in the story of Mars exploration. I hope you will join us to continue this extraordinary journey.

Eric E. Ianson
Director, NASA Mars Exploration Program

EXECUTIVE SUMMARY

This document lays out a visionary plan for the next 20 years of NASA's Mars Exploration Program (MEP). This Plan is designed to maintain and advance U.S. leadership in Mars science exploration, a role that NASA has successfully played for over 50 years. It strategically enables NASA's MEP to respond to the National Academies Planetary Science and Astrobiology Decadal Survey *Origins, Worlds, and Life* (OWL, 2023) call for a program plan that:

- Makes steady progress toward high-value decadal-class scientific goals, with a cadence that allows rapid response to discoveries;
- Constructs an orderly sequence of missions that feeds science and technology forward, while nurturing partnerships and interactions with international, commercial, academic, and professional communities;
- Provides programmatic balance with small- and medium-class missions, as well as missions of opportunity, to maximize scientific progress;
- Establishes a stable programmatic paradigm that offers flexibility in which content, opportunity, and schedule are variables to be managed against a sustained budget level; and
- Ensures advancement through technological and educational foundations for the next generation of scientists and engineers.

The MEP 2024–2044 Plan bridges the transition from an era of solely robotic exploration of Mars to the first human missions to Mars and an eventual sustainable human/robotic presence. Focusing on MEP's science role, the Plan significantly contributes to fulfilling NASA's Moon to Mars (M2M) Strategy and Objectives Development (2023), in cooperation with other NASA Directorates and shared with many nations working in partnership and peace to take humanity's next leap.

This MEP 2024–2044 Plan is more than an invitation to participate. An affordable, achievable, and balanced Mars program depends on strong bonds within NASA, with the commercial sector, and with other national and international organizations motivated to advance aspirations held in common. At its heart, this Plan fosters inclusive participation among diverse individual, organizational, disciplinary, cross-sector, and international participants. Diversity spans individual backgrounds and areas of expertise, small and large organizations, government and industry partners with both emerging and demonstrated experience in spaceflight, and a host of

> *MEP’s guiding 2024–2044 themes address scientific investigations of great consequence that address time-sensitive questions and incrementally build toward the capacity to study Mars systemically, the way we study Earth.*

other capabilities that can be brought together on behalf of discovery. It seeks to make the experience of exploration highly accessible by individuals and communities worldwide, all while honoring MEP’s role in the respectful stewardship of Mars as it continues to lead, and collaborate in, exploration on behalf of humanity.

MEP’s past performance demonstrates that a two-decade programmatic plan provides enough time to yield results and sufficient structure and guidance to concentrate resources for high-priority, Agency- and science-community-defined objectives. In the past two decades, MEP’s evolving science themes (*Follow the Water, Explore Habitability, Seek Signs of Life, Prepare for Human Exploration*) successfully enabled readiness for Mars Sample Return (MSR), the highest science-community priority for planetary science for three decades, while meeting high-priority objectives associated with MEP’s four science goals (in brief, *Life, Climate, Geology,* and *Human Exploration*). MEP’s programmatic planning in the 2024–2044 period focuses on three co-equal, guiding themes: exploring the potential for **Martian life**, supporting the **human exploration** of Mars, and revealing Mars as a **dynamic planetary system** (Figure 1).

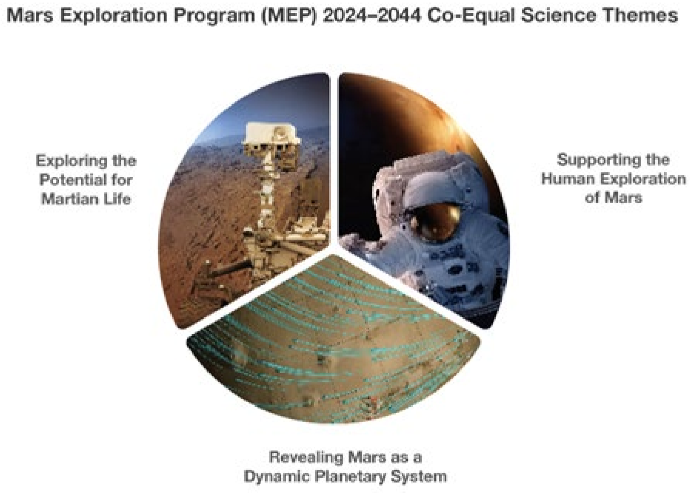


Figure 1. MEP 2024–2044 co-equal science themes. *NASA/JPL-Caltech*

These 2024–2044 science themes recognize that Mars exploration is at a scientific crossroads and a programmatic inflection point; both junctures require targeted planning and agility in meeting the challenges and opportunities inherent in the changing nature of Mars exploration.

Mars Exploration at a Scientific Crossroads: Time-Sensitive Investigations

Search for Life. Based on its programmatic achievements over the past two decades, MEP, NASA, and its partners are on the verge of achieving the aspiration of its prior 20-year plan: the return of Martian samples for study in Earth laboratories, using sophisticated equipment to detect potential signs of any microbial life on Mars (Figure 2). If researchers were to detect and validate any signs of ancient life in the samples, this discovery would transform our understanding of the prevalence and role of life in our universe, with profound implications for science and humanity as a whole. It would likely have a transformative effect on both robotic and human exploration. Even without the detection of ancient life in the samples, these types of observations would inform future directions of scientific inquiry and potential Mars missions. Having demonstrated first-of-a-kind capabilities in landing and roving on Mars and long-term orbital campaigns, MEP must extend its capabilities to reach more scientifically compelling, less accessible locations. In these places, the potential to understand possibilities for both past and present microbial life, the geologic and climatologic history of Mars, and its habitability are perhaps even greater.

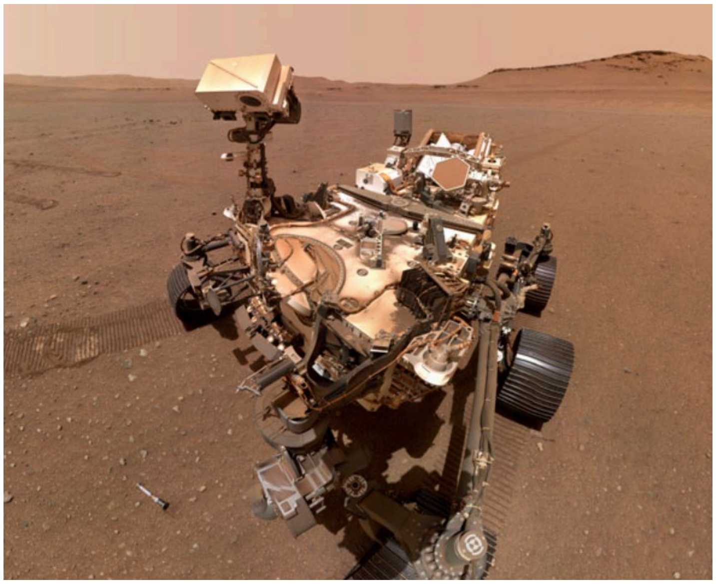


Figure 2. Robotic sample science. Mars rover *Perseverance* gazing down on a tube containing a Mars sample for prospective return to Earth. *NASA/JPL-Caltech*

NASA has only explored a handful of in situ locations on Mars, which do not adequately represent the diversity of the Martian surface. These areas have relatively safe landing sites and environments that record a narrow window of Martian history. The rock record at these sites covers a transitional period between the early, warm, and wet environment most conducive to the establishment of life as we know it, and the later, colder, and drier conditions akin to those observed today. Orbital data indicate diverse and successive episodes of habitable environments on early Mars. In searching for signs of early life, it is desirable to peer back into Martian history to characterize the environment when Mars was much more Earth-like. That presents a clear opportunity for future Mars exploration to define the history and scale of change during the transition to present-day Mars.

Any potential oasis for present life or preservation of ancient life are likely located in terrains that have historically been more challenging to access. Some of the most fascinating landscapes on Mars, for example, are found in the southern hemisphere, where the mean surface elevation has prevented robotic spacecraft from landing by traditional means. These southern highlands preserve the state of the Martian crust of 4 billion years ago, precisely when Mars was likely most hospitable to life (comparable to the timeframe in which we see evidence of the earliest life on Earth). Other locales providing conditions potentially conducive to life include the subsurface (including caves, subsurface ice deposits, and volcanic environments), where suitable chemistry and environmental conditions may have allowed life to gain a foothold. MEP is rapidly advancing technologies to overcome the technical challenges to enable exploration in these scientifically compelling locales.

> *MEP has a small window of opportunity to seek life in a pristine Martian environment, as human exploration may be possible as early as the late 2030s, following successes at the Moon.*

Novel technologies to reach unique areas of astrobiological interest are maturing at a critical time. With human exploration on the near horizon, MEP has very limited time remaining to conduct science in a pristine Martian environment, free from the biological influence humans would inevitably bring to Mars, even with enclosed systems (e.g., suits, habitats, vehicles).

Human explorers would carry with them vast amounts of Earth-based microbes that are a natural part of the human biome and essential to healthy bodily functions. These microbes could potentially survive, adapt, and spread on Mars. It would not be possible to reduce these Earth-based microbial populations in the same manner as that for robotic missions (e.g., through heating and sterilization processes). Therefore, without a better understanding of how life from Earth may spread or survive on the Red Planet, a human presence could complicate Martian life-detection efforts.

MSR, an international collaboration between NASA and the European Space Agency (ESA), is designed to return to Earth a scientifically selected set of Mars samples for investigation to enable our understanding of Mars, including the advancement of the search for ancient life. The Decadal Survey (OWL, 2023) recommended a robotic extant-life-seeking mission as the next medium-class MEP mission after sample return. While this Mars Life Explorer (MLE) mission concept recommended a mid-latitude location with near-surface, accessible ice (potentially characterized by an ice-mapping mission per OWL, 2023), MEP will continue to assess the best location for an extant-life-seeking mission on the Martian surface that would also address central questions related to the geological and climatological history of Mars and habitable conditions through time. While such a mission would provide insights into our understanding of any potential biological history at Mars, it, along with MSR, is but a subset of a complete assessment of the potential Martian biosphere, both past and present.

> *Driven by Mars science community priorities, MEP has a central leadership role in defining the highest priority science investigations to be pursued by future astronauts, as well as optimal candidate locations for those investigations.*

Support for Human Exploration. With NASA and commercial advances in observing the Earth and exploring the Moon, human missions to Mars are on the horizon. Driven by Mars science community priorities, MEP has a central leadership role in defining the highest priority scientific investigations that human explorers would enable (particularly with the larger and more complex facilities and equipment that would accompany them, Figure 3), as well as the best locations for those investigations.

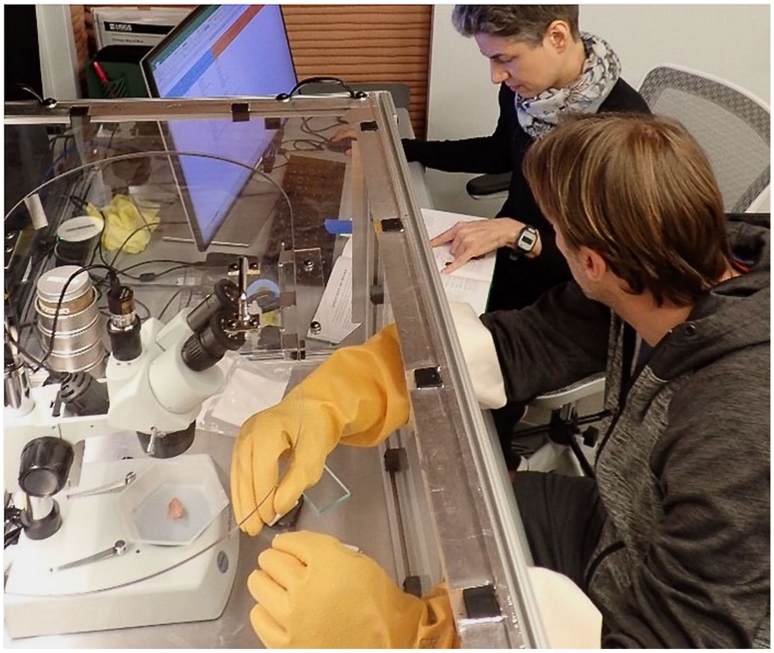


Figure 3. Simulating in situ science on Mars. Crew members in a year-long Mars analog mission study simulated Mars samples using the glovebox inside the habitat. *NASA/CHAPEA Crew*

While conducting robotic missions for fundamental science, MEP can advance precursor science for human exploration in collaboration with other NASA Directorates and external partners. Such data would help reduce the costs and risks of future human exploration, while increasing the performance of human-class systems. Given its experience in characterizing sites for high-priority robotic scientific investigations, MEP can provide insight into candidate sites for human exploration that contain both scientific and resource regions of interest (OWL, 2023). Collected Mars mission data for fundamental science (including sample science) for such candidate sites can also assist mission planners in designing safer landing approaches and traverse routes; identifying environmental conditions that could impact surface operations and human health and safety; and, critically, determining the availability of Martian resources (e.g., water ice and other minerals for propellant, life support, construction materials, and eventually, agriculture) that would alleviate a dependence on Earth's resources.

Revealing Mars as a Dynamic Planetary System. The success of prior missions demonstrates that Mars is a much more dynamic and diverse place than anticipated, with numerous mysteries still to be resolved. With aging spacecraft that have lived far beyond their anticipated lifetimes, MEP's long-term weather, imaging, and other remote-sensing assets are under threat. These spacecraft have demonstrated the scientific and operational value of providing a continual record of Mars' ever-changing environment and context relevant to the science and/or operations of all Mars missions.

Taking an interconnected, dynamic systems view—seeing Mars as an ever-changing whole—depends on increasingly studying Mars the way we study Earth. On our home world, vast networks of spacecraft continuously acquire complementary and often coordinated data on the ground, in the air, and from orbit. The challenge for Mars is how to enable such extensive research across the entire planet in an affordable, optimal way, approaching as much of the depth and breadth as needed to answer the most pressing questions about Mars and planetary processes. These capabilities are necessary for:

- making Earth-Mars comparisons that help reveal the workings of our home planet;
- understanding the evolutionary paths of Mars, Earth, and planets in our solar system and around other stars; and
- contributing to an understanding of changing surface and atmospheric conditions on a planet human explorers will soon inhabit.

Interconnections Among the 2024–2044 Science Themes. These three science themes for Mars exploration have multiple overlaps. MEP seeks to optimize the nation's return on investment in Mars exploration by simultaneously addressing highest priority science investigations that are unique to each, as well as identifying synergies where multiple theme-relevant objectives can be met. The three themes share in common: reaching and exploring the most scientifically compelling places, systemically studying Mars the way we study Earth, and returning high-volume data to increase the potential for discovery, all of which inspire maximum participation in this Plan.

Mars at a Programmatic Inflection Point

With these ambitious scientific priorities, MEP finds itself at a programmatic inflection point, with challenges and opportunities that require new approaches for the Program's continued success in the 2024–2044 period:

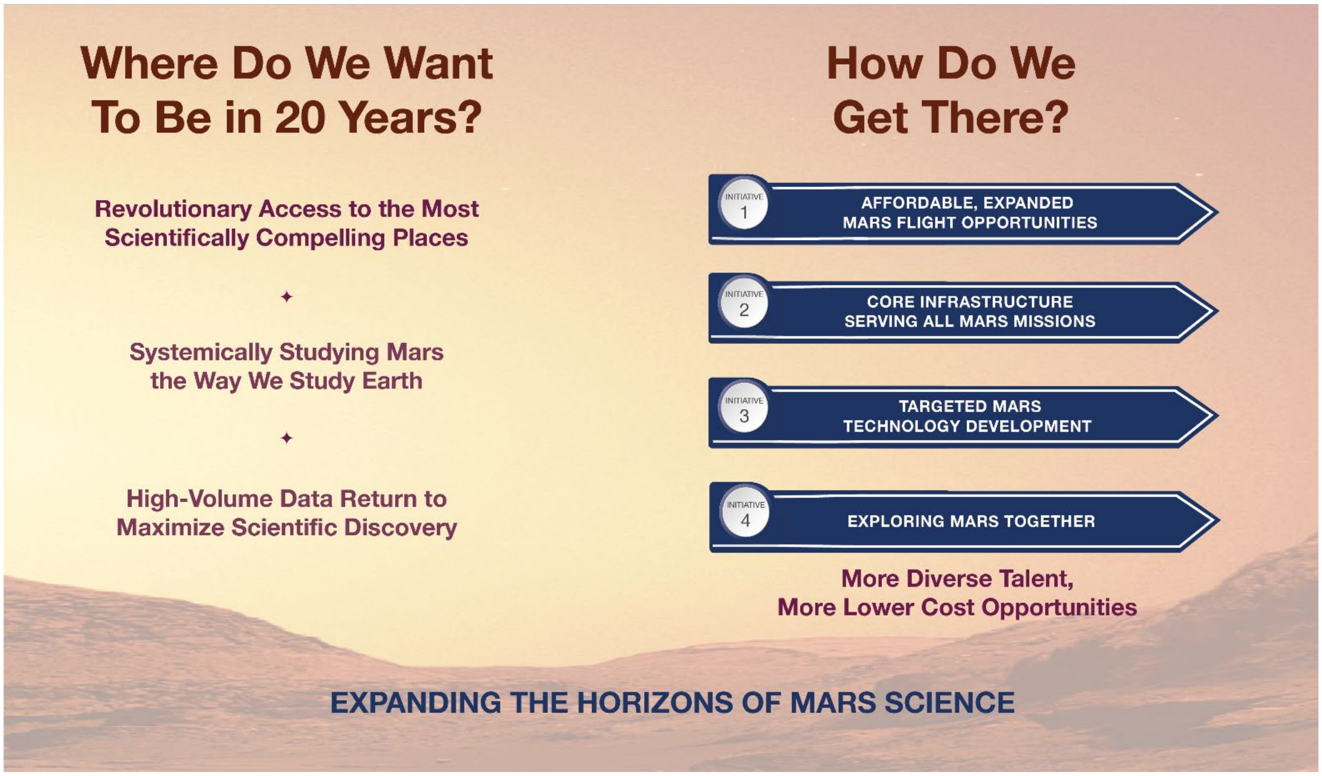
- living within a highly constrained budget in the MSR era, given the immense complexities, yet high value, of that long-awaited international campaign;
- shifting toward more frequent, yet affordable, missions that rely on standardized parts and interfaces;
- establishing a stable program-level budget that can accommodate multiple MEP priorities and that have the flexibility to adjust schedules to address budget constraints;
- leveraging the emerging capabilities of industry in new models of public-private partnerships that develop lower-cost commercial services; and
- strategically working with international space agencies with common scientific and technological goals, while managing the complexities of differing budget cycles.

Recognizing these challenges and opportunities, to make as much scientific progress as possible, MEP is structuring its activities for the next 20 years under four initiatives (Figure 4) that provide guidance for implementation.

1) *Affordable, Expanded Flight Opportunities:* Establish a regular cadence of science-driven, lower-cost mission opportunities as a new element of the MEP portfolio to address the breadth of outstanding Mars questions and to enable increased participation by the diverse Mars science community.

> *While maintaining a sustainable program-level budget, MEP seeks to develop more frequent and affordable Mars missions, improve infrastructure, enable game-changing technologies, and broaden participation.*

2) *Core Infrastructure Serving All Missions:* Enable infrastructural advancements that no single mission could likely achieve alone and that lower the costs and risks of, and increase benefits for, all Mars missions. Actively consider opportunities to buy commercial services to address MEP infrastructure goals.



Where Do We Want To Be in 20 Years?

Revolutionary Access to the Most Scientifically Compelling Places

✦

Systemically Studying Mars the Way We Study Earth

✦

High-Volume Data Return to Maximize Scientific Discovery

How Do We Get There?

INITIATIVE 1 AFFORDABLE, EXPANDED MARS FLIGHT OPPORTUNITIES

INITIATIVE 2 CORE INFRASTRUCTURE SERVING ALL MARS MISSIONS

INITIATIVE 3 TARGETED MARS TECHNOLOGY DEVELOPMENT

INITIATIVE 4 EXPLORING MARS TOGETHER

More Diverse Talent, More Lower Cost Opportunities

EXPANDING THE HORIZONS OF MARS SCIENCE

Figure 4. Aspirations of the MEP 2024–2044 Plan. Four initiatives will lead to the ability to reach scientifically compelling places, to study Mars the way we study Earth, and to enable high-volume data return to maximize discovery. *NASA/MEP*

3) *Targeted Mars Technology Development:* Continue improving the capabilities of science-enabling missions that collectively enhance U.S. leadership in Mars exploration, lower the costs of all Mars missions, and build on the developments and experience gained from Earth-observing and M2M lunar missions.

4) *Exploring Mars Together:* Strengthen MEP activities that support NASA's goals to develop partnerships; to train, sustain, and retain a qualified and diverse workforce; to develop scientific and technical literacy; and to foster a more inspired and informed society.

A program inclusive of these four initiatives increases the potential for more—and more frequent—lower-cost missions, allowing MEP to address a wide range of planetary science priorities through missions that collectively lead to a sustainable human-robotic presence on Mars; expanded U.S. academic, commercial, and international leadership in Mars exploration; and greater inclusion for all communities in resulting discoveries.

MARS EXPLORATION PROGRAM

VISION

We explore Mars to understand its past and present, the potential for life, our place in its future, and its lessons for our home planet.

MISSION

Advance U.S. scientific, technological, commercial, educational, and inspirational leadership in the evolving robotic, and eventually human-robotic, exploration of the Martian system.

IMPLEMENTATION

NASA's Mars Exploration Program explores our nearby, habitable planetary neighbor, providing a continuous flow of scientific knowledge through discovery-driven missions and high-value partnerships that leverage both robotic and, eventually, human explorers.

MEP VALUES

BALANCE	Employ a mix of lower-cost and medium-class missions that together maximize progress toward the scientific goals envisioned by the Planetary Science and Astrobiology Decadal Survey (OWL, 2023), other relevant community- and stakeholder-based input, and continued mission- and research-based results. Provide a combination of mission-enabling infrastructure, technologies, and research that advances lower-cost community-prioritized opportunities.
INNOVATION	Develop new mission concepts, nurture the research and technical community, and engage in appropriate collaborations with international, commercial, and academic partners to ensure an orderly sequence of missions and activities that systemically meet high-priority scientific goals.
AGILITY	Structure programmatic management and implementation practices to respond rapidly to scientific discovery, technological innovation, and emergent and evolving stakeholder and community priorities.
RESILIENCE	Provide programmatic management strategies and practices that ensure stability and resilience under inevitable budgetary perturbations and technical setbacks.
INCLUSIVITY	Create a culture of respect and encouragement to maximize the talent and ideas brought to Mars exploration and enrich personal and community relationships. Build human capacity to contribute to a shared future on Mars, including the development of the next generation of planetary scientists and engineers from diverse backgrounds.
INSPIRATION	Share knowledge for humanity through direct and personal experiences of Mars and Mars Exploration and promote the value of peaceful, scientific exploration of Mars.
ACHIEVABILITY	Provide aspirational plans that will generate scientific and technological breakthroughs worthy of the nation’s investment in Mars exploration and that will be flexible and scalable enough to be realistic within program and mission constraints.
AFFORDABILITY	Enable other NASA, international, and commercial cost- and risk-sharing opportunities by leveraging commercial capabilities, investing in emerging technologies, developing new business models, and developing programmatic innovations such as missions of opportunity and piggyback/rideshare potential.
ACCOUNTABILITY	Implement program-evaluation practices that build MEP’s capacity to ensure the highest return on the nation’s investment in Mars exploration.

MEP FOUNDATIONAL PRIORITIES

Implement a Mars program that addresses prioritized science objectives as defined by the science community, in support of MEP’s science goals and the recommendations of the Decadal Survey (OWL, 2023).

Continue support for MEP’s existing Program of Record.

Initiate Mars flight opportunities at the first opportunity afforded by the MEP budget.

Compete lower-cost missions, including hosted payloads, as early as possible.

Explore lower-cost commercial services (e.g., delivery of spacecraft, hosted payloads, communications relay, and high-resolution imaging), while managing the risks associated with emerging new industry capabilities.

Partner with international space agencies and commercial entities on missions of opportunity, rideshares, and collaborative joint missions.

Support work to obtain data relevant to a search-for-life mission and to enabling future human-led surface science and operations.

Replenish critical infrastructure at Mars to maintain continuity of critical data and to support new lower-cost missions advancing MEP science themes.

Invest in technology development and research efforts to enable science.

Develop and implement opportunities to increase access to knowledge, build relationships, and provide participative activities at Mars for diverse communities.

1 BACKGROUND

1.1 WHY MARS?

Mars has held the interest and imagination of humanity for millennia, from the myths of ancient civilizations to the robotic missions of our present age and on toward realizable visions of humans and robots working together on the Red Planet. Beyond our home planet, Mars has the most Earth-like surface conditions in our solar system. It is an accessible destination where humanity can address some of the most profound questions in science.

The Martian rock record uniquely preserves conditions of the early solar system, particularly during the period when we find the first evidence of life on Earth. Some of the key questions that continue to drive us toward Mars as a destination include:

- Did Mars once harbor life and does it still?
- Why did the Martian environment dramatically diverge from Earth, abundant with life, despite likely similar beginnings?
- What can Mars teach us about our home world and planetary formation, processes, and evolution in our solar system and beyond?
- How can a human presence transform scientific discovery and what do we need to know about the Martian environment to enable humans to survive and sustain a presence on Mars?

Answering these complex questions compels a strategic emphasis on collaboration across:

- a growing multitude of scientific disciplines (planetary science, astrobiology, human health, biological and physical sciences, geotechnical engineering, and other environmental sciences for human mission planning);
- Earth, Moon, and Mars endeavors;
- both leading and emerging spacefaring nations;
- mission-enabling businesses in the commercial space sector;
- all levels of academia; and

- intergenerational communities worldwide for whom Mars exploration is ultimately conducted.

By adopting the initiatives described in this MEP 2024–2044 Plan as a guiding philosophy, NASA is committed to continuing the exploration of Mars by creating opportunities for engaging diverse talents and capabilities to achieve an affordable, discovery-driven program for the next two decades.

1.2 ROLE OF NASA'S MARS EXPLORATION PROGRAM (MEP)

NASA's Mars Exploration Program (MEP) consists of an interconnected set of missions and activities with scientific, technological, and strategic synergies and feed-forward capabilities that mutually work toward achieving the Mars Exploration Program Plan's scientific goals (last approved in 2021):

GOAL I:	Determine if Mars ever supported, or still supports, life.
GOAL II:	Understand the processes and history of climate on Mars.
GOAL III:	Understand the origin and evolution of Mars as a geological system.
GOAL IV:	Prepare for human exploration.

Organizing Mars exploration efforts so that they provide the highest scientific payoff for the nation's investment is a priority for NASA, its stakeholders, and, ultimately, the U.S. general public. To ensure intensive input from the science community that is responsive to discovery, the Mars Exploration Program Analysis Group (MEPAG) periodically refines community science goal statements and defines related objectives, subobjectives, and prioritized investigations that trace to them. Findings of the Planetary Science and Astrobiology Decadal Survey (OWL, 2023) provide strategic priorities for NASA's Planetary Science Division, including the MEP. MEP is responsive to, and organized for, the achievement of these community-based scientific interests and related Agency initiatives (e.g., M2M, 2023).

> *Demonstrating science and technology "feed forward," the MEP 2024–2044 Plan builds on outcomes from the past two decades to expand U.S. success in Mars exploration for generations worldwide.*

MEP is discovery-responsive in that the scientific data and discoveries of one mission influence the objectives and design of future missions. The accumulated knowledge and assets from prior MEP activities feeds forward scientific knowledge and engineering capabilities that support multiple other Mars missions. To build an integrated program structure, MEP invests in crosscutting functions, including research, infrastructure (e.g., telecommunications relay, high-resolution surface imaging from orbit), technology, data analysis and visualization, and public engagement. MEP also collaborates with commercial, academic, and international partners to achieve its goals. The Program is committed to maintaining sufficient flexibility to address both programmatic opportunities and issues presented by its highly complex missions, while advancing U.S. leadership in Mars exploration.

1.3 PRIOR SCIENCE-DRIVEN MEP THEMES AND ACHIEVEMENTS

Since its inception in 2000, MEP has successfully developed an evolving set of programmatic themes (Figure 5) that guide and connect the science of Mars missions. This strategy enabled missions to build on the scientific and technological advances of those that came before, while also providing programmatic flexibility in being responsive to discoveries and innovations. Through its scientific and engineering progressions, MEP has found significant success in this theme-based approach, finding environments conducive to supporting life and enabling sample science, including the potential to detect biosignatures. The return of carefully selected high-

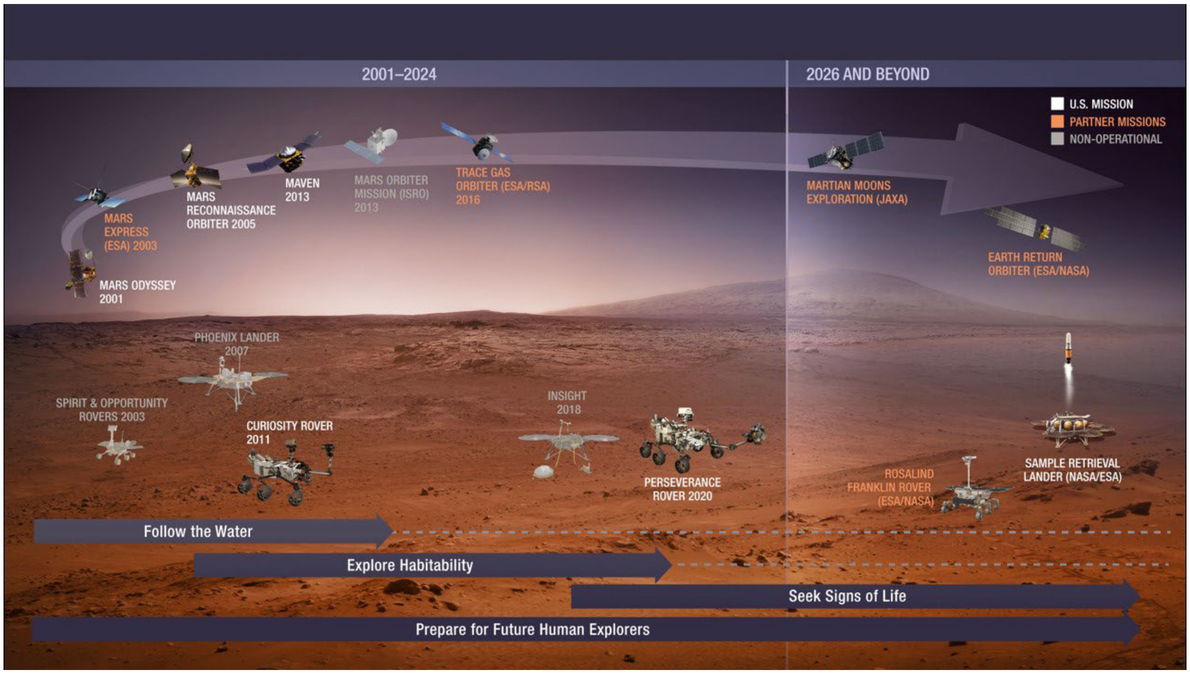


Figure 5. MEP 2001–2023 Themes and Missions. *NASA/MEP*

value scientific samples from Mars via Mars Sample Return (MSR) represents the culmination of decades of work across these themes.

Follow the Water. The Viking missions to Mars demonstrated the difficulty of detecting life in a largely unknown environment. Thus, before seeking life directly, MEP missions sought to understand whether and where Mars may have had liquid water long enough for life to take hold and thrive. Water is essential to life processes as we know them. The first mission in the Program, *Mars Odyssey* (ODY, launched in 2001), revealed large areas of subsurface water ice on Mars. Mars Exploration Rovers *Spirit* and *Opportunity* (MER, launched in 2003) demonstrated that Mars once had a watery past at both of their locations. ODY and Mars Reconnaissance Orbiter (MRO, launched in 2005) also contributed to selecting a hazard-free site for the *Mars Phoenix Lander* (PHX, launched in 2007), a mission that sampled water ice directly. In addition, ODY, MRO, and the European Space Agency (ESA) Mars Express orbiter detected minerals distributed across the planet, most preserved and exposed in the older terrains, that could only have been formed by the action of surface or ground water.

Explore Habitability. With evidence of long-standing water, MEP's next step was to determine whether such places also had the chemical ingredients life needs. If a site ever had water for extended periods of time as well as the necessary chemical conditions for life, it is considered *habitable*; the question remains as to whether it was ever *inhabited*. The Mars Science Laboratory (MSL, launched in 2011) *Curiosity* rover confirmed that its landing site was once an ancient crater lake. The rover's enhanced instrument suite demonstrated the presence of organic materials (the chemical building blocks of life) and a chemical environment that could sustain life. The Mars Atmosphere and Volatile EvolutioN (MAVEN, launched in 2013) mission directly measured the loss of water from the Martian atmosphere to space, which is important for understanding the history of climate and the planet's evolving habitability through time.

Seek Signs of Life. Having established that Mars had both water and chemistry suitable for life, MEP sent the Mars 2020 (M2020, launched in 2020) *Perseverance* rover to collect targeted samples that might contain biosignatures of ancient microbial life. The return of samples to Earth through the MSR campaign would advance this critical chapter in Martian exploration. The past three decadal surveys cited Mars sample return activity as the highest planetary and astrobiological scientific priority, and of fundamental and strategic importance to NASA and its international partners.

Prepare for Human Exploration. From ODY's early measurements of the radiation environment to *Perseverance*'s successful demonstration of atmospheric in situ resource utilization (ISRU), the endurance of astronaut suit materials, and more, MEP missions have contributed to studies of the Martian environment to assist human-mission planners in designing systems to deploy, protect, and enable human explorers. With human exploration now on the horizon, future MEP missions would provide opportunities for observations that serve both fundamental science and applied science for human exploration (M2M, 2023) as part of a sustainable and synergistic human-robotic future.

1.4 A PROGRAMMATIC PARADIGM SHIFT: THE NEXT PHASE OF MARS EXPLORATION

Now at a programmatic inflection point, MEP must assess its next scientific pathways in the context of:

- the MSR campaign;
- a changing space business environment with growing international and commercial interests and capabilities;
- previously described time-sensitive scientific research prior to human arrival;
- contributions to the realization of NASA's Moon to Mars (M2M, 2023) endeavor;
- an aging telecommunications, imaging, and weather infrastructure at Mars; and
- other challenges and constraints.

Paradigm Shift—Lower-Cost Missions. The wider context in which Mars exploration takes place requires a major shift in the way MEP organizes for maximal scientific, technological, and societal benefit. To remain a vanguard in Mars exploration, MEP must embrace a new, different model: the ability to send more—and more frequent—missions to Mars in an affordable and achievable manner, and to do so while cultivating a diversity of talent and engaging the public in opportunities to explore Mars.

In advancing decadal-class science, MEP intends to meet, within a stable budget profile, both the growing demand for mission opportunities by the scientific and technical Mars community and the critical need to replenish an aging Mars infrastructure. For Program viability in future years, MEP must transition to lower-cost, more frequent missions that are more individually targeted on a specific investigation, yet collectively contribute to highest priority Mars scientific objectives. Frequent, lower-cost flight opportunities would enable greater inclusion for individuals and institutions, payload innovation, and response to prior discoveries. They would also enable replenishment of assets and/or the development of networks, with replicas sent at different times. Networks that enable systems science with more coverage of Mars, more frequent observations, and complementary measurements have long been an aspiration of the Mars science community and are relevant to studying Mars the way we study Earth.

> *Leveraging significant investments in Earth, the International Space Station (ISS), and lunar commercial services, MEP can focus on relatively small investments to adapt commercial services for Mars.*

To enable frequent, lower-cost Mars missions (from smallsats to medium-class missions), programmatic investments in Mars infrastructure recognize that some capabilities are crosscutting, benefitting multiple MEP missions. For example, the availability of common-use infrastructural assets (e.g., delivery systems capable of carrying multiple payloads, communications-relay capabilities, and high-resolution imaging) would be major facilitators in developing affordable, focused Mars missions, including those with next-generation sensors returning high-volume data. When possible, in cooperation with international and commercial partners, MEP will support the development of standardized, replicable, and interoperable hardware and software for spacecraft so that they can be replenishable and upgradable over time. These measures would not only lower the costs of this new class of focused missions, but also make medium-class missions requiring more complex instrument suites more affordable and achievable as well.

With both infrastructural investments and targeted technology developments, it is entirely within reach—and within the scope of this Plan—to be able to access nearly all of Mars, to build toward systemically studying Mars the way we study Earth (including eventual networks built through multiple lower-cost opportunities), and to return high-value, high-volume data, thereby enabling our ability to answer key decadal-class questions.

Paradigm Shift—Commercial Services. Exploring Mars together through new partnership models with the international, commercial, and academic communities is essential. Prior government and industry investments have significantly matured commercial spacecraft and services for Earth and lunar applications. Based on recent commercial services studies and industry workshops, MEP anticipates a real potential to leverage commercial capabilities and economies of scale for lower-cost Mars missions, much as NASA is accomplishing through other innovative public-private partnership solutions such as Commercial Orbital Transportation Services (COTS) and Commercial Lunar Payload Services (CLPS). Adapting industry’s near-Earth and lunar capabilities for Mars (e.g., its distance, radiation environment) is comparatively less difficult to achieve in both cost and complexity, and thus programmatically achievable within 20 years. Guidance from the science community on key aspects of commercial service capabilities will remain central.

Figure 6. Example of emerging commercial partnership potential. In February 2024, NASA collected scientific data from the first successful commercial Moon lander, enabled through NASA's CLPS initiative. A similar public-private partnership model could be developed for Mars, potentially lowering costs for future MEP missions. *Intuitive Machines*

By acting as an early anchor investor through initial public-private partnership phases to tailor existing Earth/Moon service models for Mars, MEP could establish critical infrastructure (e.g., spacecraft delivery and hosting, telecommunications, and high-resolution imaging) that serve multiple next-generation, lower-cost Mars missions, and by extension, deep-space missions throughout the solar system. Such lower-cost missions would provide multiple benefits: more affordable, more frequent opportunities for discovery and support for sustained U.S. economic leadership in the deep-space sector.

Over time, the growing international demand for Mars services could also provide a wider and more sustainable customer base for U.S. commercial Mars services. With an increased number of customers, Mars mission costs could be reduced even more in future years through cost-sharing, especially when industry providers have excess capacity (e.g., shared rides, data delivery). In addition, in support of M2M (2023) ambitions, minor adaptations needed for Mars could be built into the early design of lunar systems. That upfront inclusion could save NASA costs in the long run, as redesigning systems for Mars later in the process would likely be far more expensive.

Paradigm Shift—Human Exploration. Mars exploration will soon experience the arrival of humans at Mars and, eventually, a sustained human-robotic presence there. Building on lunar exploration experiences, the capabilities that humans can bring is transformative for science investigations and deeply profound as we take the first steps to living, working, and exploring far beyond our home planet.

In support of this future, the Mars scientific community is essential in defining the future science that would benefit from the presence of humans and human-class infrastructure, as well as in characterizing potential scientific and resource regions of interest. This Plan is aptly named *Expanding the Horizons of Mars Science* as the science of Mars is inevitably expanding to include many more fields. A broader Mars science community can contribute beyond its primary advancement of foundational disciplines of planetary science and astrobiology to include human biology and physics that protect the health of future human explorers, space weather and forecasting, agricultural science, and other disciplines. The knowledge gained can inform ISRU, civil engineering, and other operational needs.

While research objectives can differ across scientific disciplines, the science itself is often highly synergistic. Seeking ways to optimize multiple outcomes and cross-disciplinary interactions can result in higher returns on investment and contribute to sustainable human-robotic presence on Mars. For example, obtaining data about the Martian environment for fundamental science could also fill knowledge gaps to enable the development of human-class systems with long-lead design timeframes and to provide insights about the science humans will do once there.

Paradigm Shift—International Mars Ambitions. The growing Mars community extends well beyond the United States. NASA is no longer one of the few with focused Mars exploration ambitions. Representing both experienced and emerging spacefaring nations, dozens of space agencies have joined international working groups focused on Mars exploration to promote their own and shared interests, and largely see multilateral collaboration as a means of achieving objectives affordably.

1.5 PURPOSE OF THE MEP 2024–2044 PLAN

Per *Origins, Worlds, and Life* (OWL, 2023), Mars continues to pose key questions that call for a coordinated program of scientific exploration. Under the framework of its vision, mission, values, and foundational concepts, MEP will implement its current Program of Record (existing Mars missions, the NASA contribution to the ESA ExoMars Rosalind Franklin Mission, and the Sample Receiving Project [SRP], along with other programmatic activities) and design and develop strategic initiatives and missions that support and sustain NASA and the nation’s ambitions for Mars exploration. While this Plan is created for a NASA Science Mission Directorate (SMD) program, it requires close coordination with many organizations, including other SMD Programs, NASA’s Exploration Systems Development Mission Directorate

(ESDMD), Space Operations Mission Directorate (SOMD), and Space Technology Mission Directorate (STMD).

In developing a balanced portfolio of missions with both budget stability and the potential to generate a steady stream of discoveries, this MEP 2024–2044 Plan must address the following questions (adapted from OWL, 2023) to align with criteria referenced in two decadal surveys for healthy planetary programs:

CAPACITY TO MAKE STEADY PROGRESS

MEP Values: Agility, Achievability, Accountability, Innovation

- Does the proposed program make reasonable progress toward the scientific goals set forth in the decadal survey?
- Is the cadence of missions and the planning process such that new scientific discoveries can be followed up rapidly with new missions?
- Does the proposed program smoothly match and complement the Program of Record, which was influenced by prior decadal surveys?

STABILITY

MEP Values: Resilience, Affordability

- Can MEP (with input from the Mars science community and commercial, international, and other partners) construct an orderly sequence of missions while meeting overarching scientific goals, developing advanced technology, sizing and nurturing the research and technical community, and providing for appropriate interactions with the international community?
- Is the program stable under the inevitable budgetary perturbations as well as the occasional mission failure?

BALANCE

MEP Values: Balance, Affordability

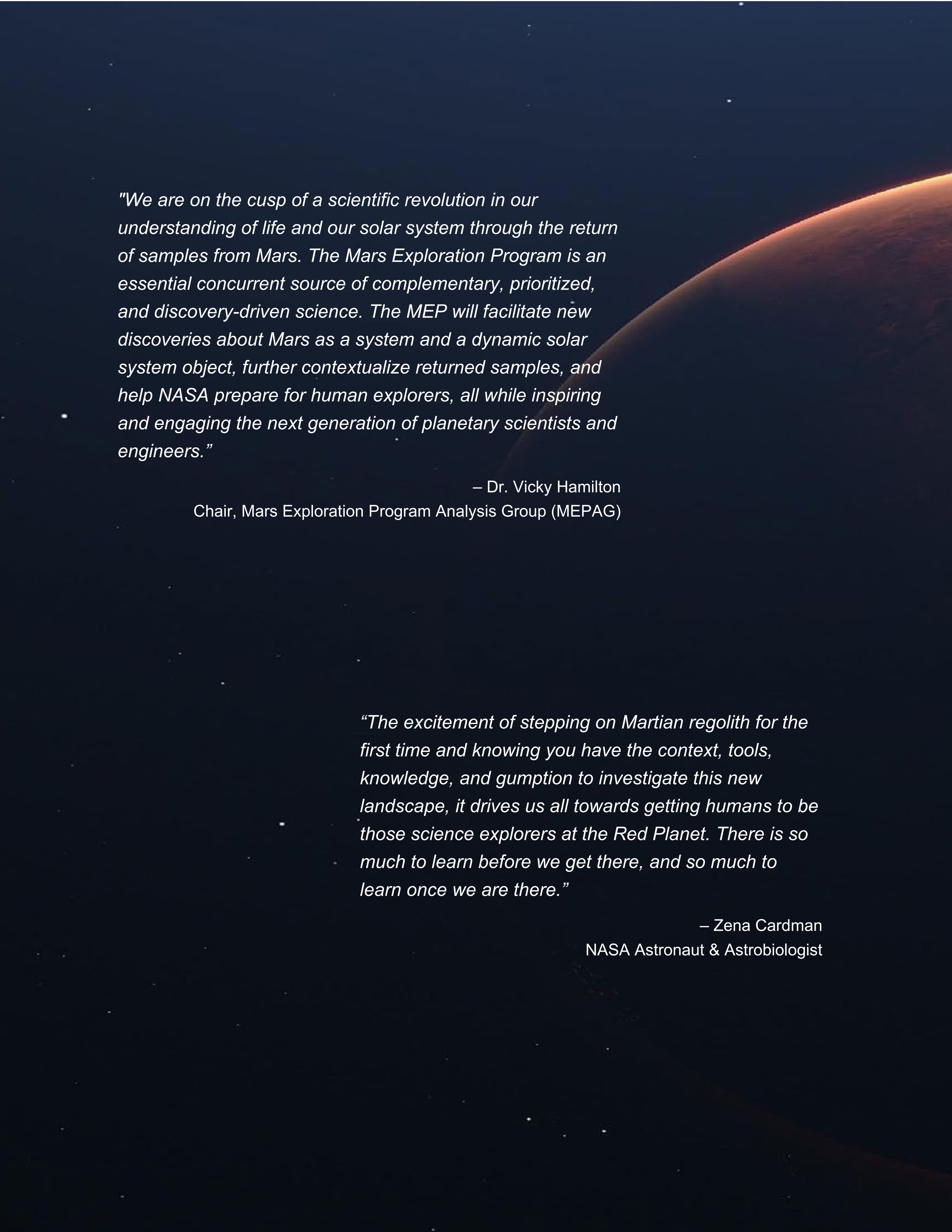
- Is the program structured to contain a mix of small- and medium-class missions that together make the maximum progress toward the scientific goals envisioned by this decadal survey?
- Can some of the scientific objectives be achieved via missions of opportunity or secondary flights on other missions?

ROBUSTNESS

MEP Values: Inclusivity, Inspiration, Innovation

- Is the program robust in that it provides opportunities for the inspiration, training, and development of the next generation of planetary scientists?
- Does it robustly lay the technological foundation for not only the present decade but also for the future?

Revolutionary thinking lies in a paradigm shift. The challenge and complexity of meeting these aims is considerable and requires as much pragmatic infrastructural, technological, and budget-conscious support as it does visionary, discovery-driven ambition. With this Plan, MEP is committed to maintaining and advancing U.S. scientific and commercial leadership in Mars exploration, leveraging emerging opportunities with diverse partners and Mars community members.



"We are on the cusp of a scientific revolution in our understanding of life and our solar system through the return of samples from Mars. The Mars Exploration Program is an essential concurrent source of complementary, prioritized, and discovery-driven science. The MEP will facilitate new discoveries about Mars as a system and a dynamic solar system object, further contextualize returned samples, and help NASA prepare for human explorers, all while inspiring and engaging the next generation of planetary scientists and engineers."

– Dr. Vicky Hamilton
Chair, Mars Exploration Program Analysis Group (MEPAG)

"The excitement of stepping on Martian regolith for the first time and knowing you have the context, tools, knowledge, and gumption to investigate this new landscape, it drives us all towards getting humans to be those science explorers at the Red Planet. There is so much to learn before we get there, and so much to learn once we are there."

– Zena Cardman
NASA Astronaut & Astrobiologist

2

PROGRAM SCIENCE THEMES FOR 2024–2044

> *Driven by science, for the next two decades, MEP will focus its systemic approach on the following co-equal science themes:*

Exploring the Potential for Martian Life

Advance the search for past and present microbial life and habitable environments through time, while developing approaches that protect both Earth and Mars.

Supporting the Human Exploration of Mars

Define the high-priority science human explorers would advance at Mars and make observations that synergistically serve both fundamental science goals and Agency objectives for the human exploration of Mars.

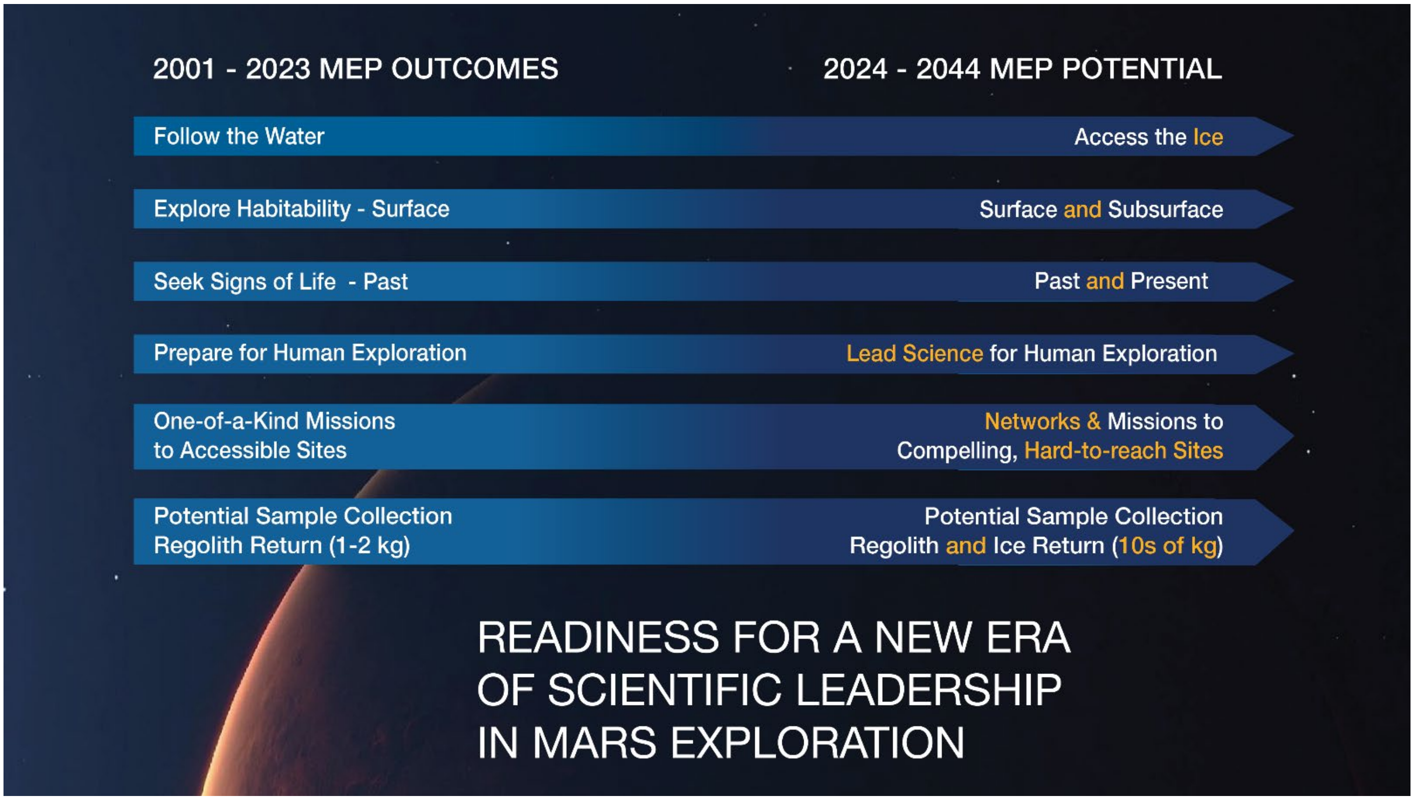
Revealing Mars as a Dynamic Planetary System

Understand the dynamic geological and climatological processes on Mars to illuminate the evolution of the Martian system, our home planet Earth, our solar system, and distant planets around other stars.

Figure 7. High-level co-equal program themes for the next two decades. *NASA*

These 2024–2044 co-equal themes (Figure 7) build on discovery-driven MEP topic areas that have guided Mars missions over the previous two decades, providing a connection to the past and a link to an equally ambitious, achievable future (Figure 8).

> *Demonstrating science and technology "feed forward," the MEP 2024–2044 Plan builds on outcomes from the past two decades to maintain and expand U.S. leadership in Mars exploration for generations worldwide.*



2001 - 2023 MEP OUTCOMES	2024 - 2044 MEP POTENTIAL
Follow the Water	Access the Ice
Explore Habitability - Surface	Surface and Subsurface
Seek Signs of Life - Past	Past and Present
Prepare for Human Exploration	Lead Science for Human Exploration
One-of-a-Kind Missions to Accessible Sites	Networks & Missions to Compelling, Hard-to-reach Sites
Potential Sample Collection Regolith Return (1-2 kg)	Potential Sample Collection Regolith and Ice Return (10s of kg)

READINESS FOR A NEW ERA
OF SCIENTIFIC LEADERSHIP
IN MARS EXPLORATION

Figure 8. Prospective programmatic progress and potential. *NASA/MEP*

2024–2044 SCIENCE THEME 1

S1. EXPLORING THE POTENTIAL FOR MARTIAN LIFE

Advance the search for past and present microbial life and habitable environments through time, while developing approaches that protect both Mars and Earth.

S1.A	**SEARCH FOR BIOSIGNATURES, PAST & PRESENT** To understand the potential for past or present life on Mars, it is important to determine whether the Martian geologic record contains biosignatures and to identify areas most likely to capture preserved biosignatures based on what is known about past and current habitability at Mars.
S1.B	**UNDERSTAND TEMPORAL & GEOGRAPHIC PATTERNS OF HABITABILITY** Studying Mars' unique ancient geologic record can reveal the extent of habitability and its temporal evolution, the existence of any present-day habitable environments in the ice-rich subsurface or other locations, and the ways in which habitable environments on Mars and Earth may have diverged.
S1.C	**EXAMINE RETURNED SAMPLES TO UNDERSTAND MARTIAN GEOLOGICAL & BIOLOGICAL PROCESSES** Returned samples increase knowledge about organic chemistry processes on Mars at global, regional, and temporal scales, the nature of any biosignatures, and the relationship between Mars' geological and potential biological history.
S1.D	**PROTECT LIFE ON MARS & EARTH** Planetary protection principles are key across our presence at Mars and upon return to Earth with samples and astronauts, especially as it relates to our search for life.

2.1 SCIENCE THEME 1: EXPLORING THE POTENTIAL FOR MARTIAN LIFE

Mars offers a unique, accessible target for investigating fundamental questions about past and present microbial life, not just on Earth and Mars, but, by extension, its potential in our solar system and beyond. Mars missions have progressively provided strong evidence of past and present habitability, yet the story of life on Mars remains unresolved. MEP aspires to understand the potential for past or present life on Mars, including determining whether the Martian geologic record contains biosignatures and identifying areas most likely to capture preserved biosignatures based on what is known about past and current habitability at Mars (S1.A). Core questions include:

- **How has the habitability of Mars evolved over the history of the planet?**
- **Did life ever arise on Mars, and if so, does it exist today?**

- **If life never developed on Mars, why not?**
- **If life once existed on Mars, but does not today, why did it go extinct?**

To answer these questions, it may be imperative to conduct some community-defined, highest priority investigations related to life before humans arrive on Mars. With human exploration on the horizon, MEP has a limited opportunity to send missions that can study Mars in its pristine state, without the inevitable biology humans would bring with them. Core to this time-sensitive priority may be scientific investigations that would aid in later distinguishing between any presumed evidence of Martian life that astronauts might detect while on Mars and any Earth-based microorganisms brought along with them. Also core to MEP is a commitment to planetary protection practices informed by international consensus standards and a respectful stewardship role in the exploration of Mars. Planetary protection principles are key across our presence at Mars, as well as upon return to Earth with both samples and astronauts (S1.D).

While MEP missions have satisfactorily determined that Mars had habitable conditions, those determinations remain somewhat localized to the specific places and geologic time periods explored robotically thus far. Studying Mars' unique ancient geologic record can reveal the extent of habitability and its temporal evolution, the existence of any present-day habitable environments in the ice-rich subsurface or other locations, and the ways in which habitable environments on Mars and Earth may have diverged (S1.B). Evidence of ancient organic material on Mars observed by rovers demonstrates that Mars can serve as a testbed for learning more about the way in which prebiotic organic chemistry may have evolved in the inner solar system, leading to life on Earth and, perhaps, on Mars. While Earth has almost entirely lost its ancient rock record to tectonism and metamorphosis, Mars retains a unique archive of ancient evidence, ready to inform our understanding of similar physical and chemical processes that initiated and sustained life on Earth (Figure 9). A range of potential prebiotic and life-bearing scenarios may have unfolded on Mars (Figure 10). Discoveries about the climatological and geologic record would provide the clues to determine which of these evolutionary paths Mars followed.

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*Building on Mars mission discoveries and technological innovation, MEP is ready to seek both past **and** present microbial life in pristine, more challenging to reach habitable environments prior to the arrival of human explorers.*

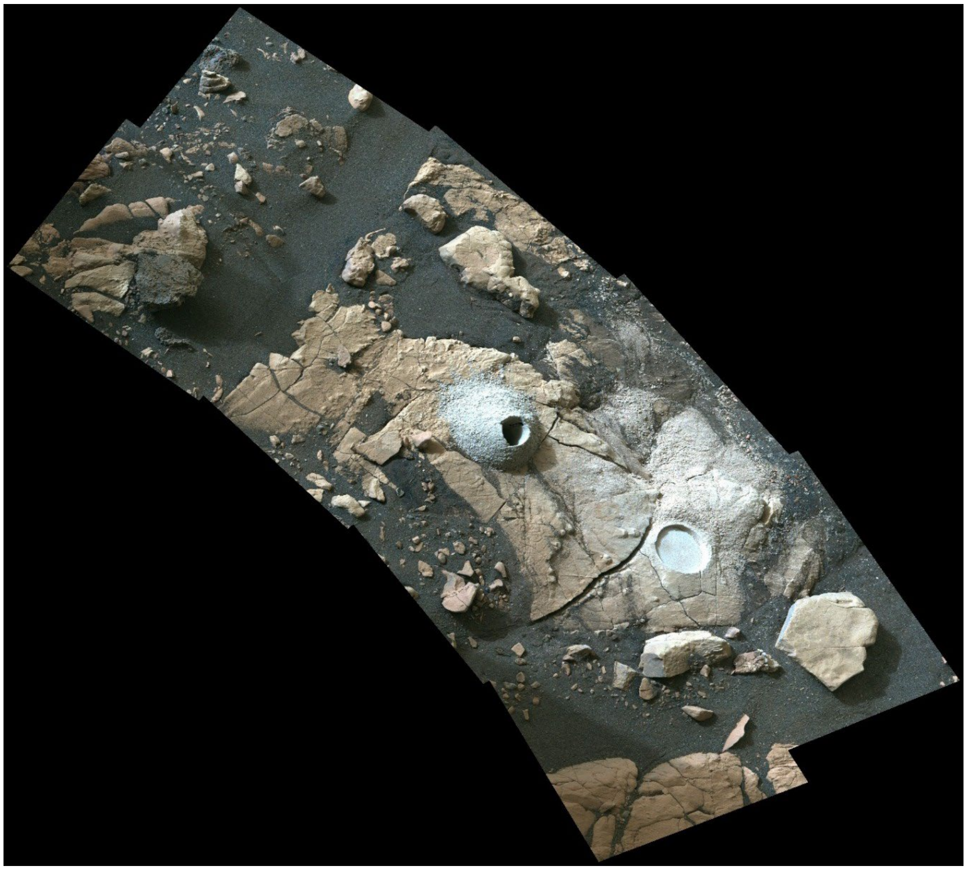
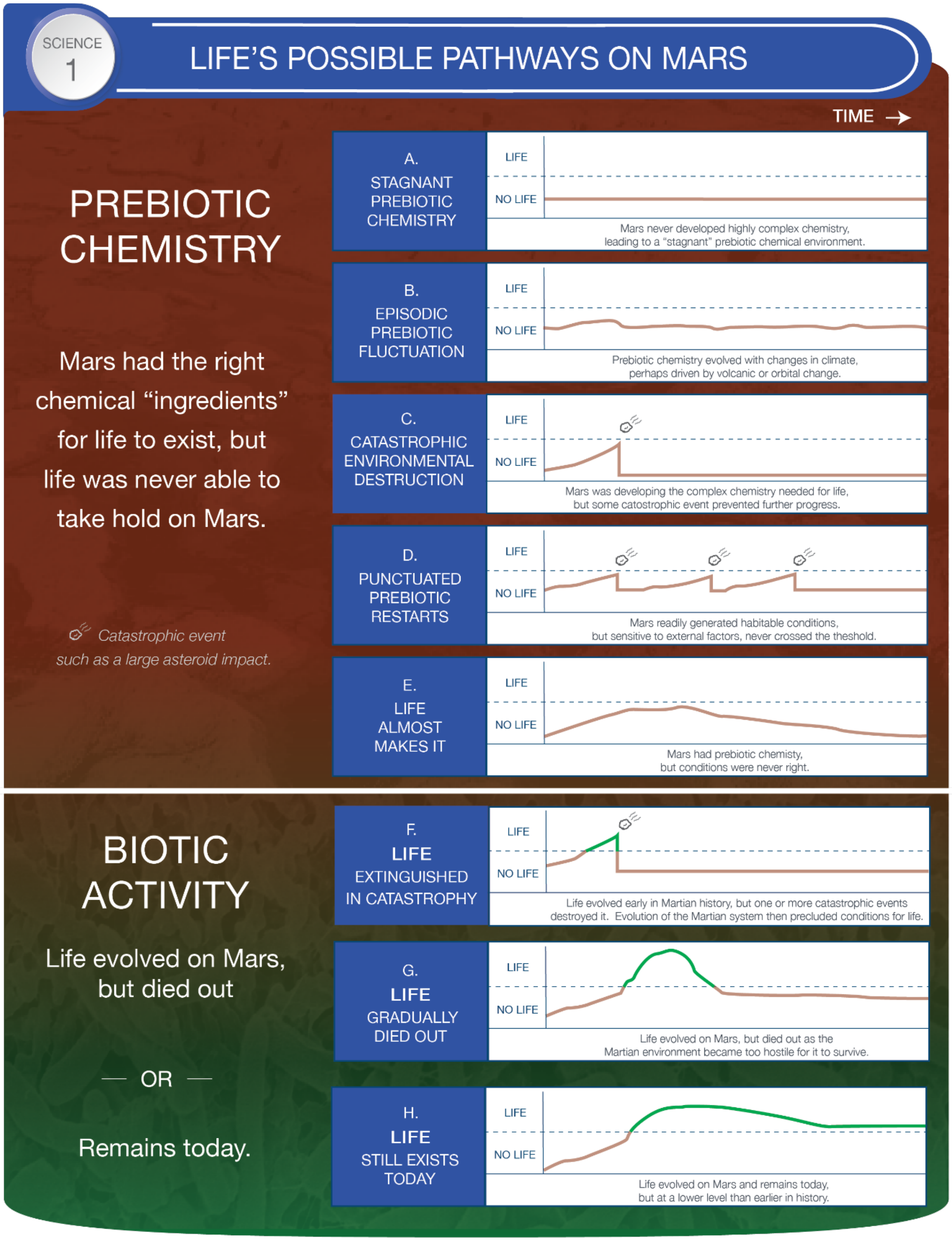


Figure 9. High-value Martian samples. Collecting samples of Martian rocks that typically preserve organic materials and other potential biosignatures significantly advances understandings of the potential for past habitable conditions and life. *NASA/JPL-Caltech/ASU/MSSS*



LIFE'S POSSIBLE PATHWAYS ON MARS

PREBIOTIC CHEMISTRY

Mars had the right chemical “ingredients” for life to exist, but life was never able to take hold on Mars.

Catastrophic event such as a large asteroid impact.

A. STAGNANT PREBIOTIC CHEMISTRY — Mars never developed highly complex chemistry, leading to a "stagnant" prebiotic chemical environment.

B. EPISODIC PREBIOTIC FLUCTUATION — Prebiotic chemistry evolved with changes in climate, perhaps driven by volcanic or orbital change.

C. CATASTROPHIC ENVIRONMENTAL DESTRUCTION — Mars was developing the complex chemistry needed for life, but some catastrophic event prevented further progress.

D. PUNCTUATED PREBIOTIC RESTARTS — Mars readily generated habitable conditions, but sensitive to external factors, never crossed the theshold.

E. LIFE ALMOST MAKES IT — Mars had prebiotic chemisty, but conditions were never right.

BIOTIC ACTIVITY

Life evolved on Mars, but died out

— OR —

Remains today.

F. **LIFE** EXTINGUISHED IN CATASTROPHY — Life evolved early in Martian history, but one or more catastrophic events destroyed it. Evolution of the Martian system then precluded conditions for life.

G. **LIFE** GRADUALLY DIED OUT — Life evolved on Mars, but died out as the Martian environment became too hostile for it to survive.

H. **LIFE** STILL EXISTS TODAY — Life evolved on Mars and remains today, but at a lower level than earlier in history.

Figure 10. Diverse potential pathways for prebiotic and biotic evolution on Mars. *NASA/JPL-Caltech*

Determining life's possible pathways on Mars contributes to answering one of the most profound questions of planetary science: ***What is the possibility of life beyond Earth?***

For nearly three decades, MEP has accumulated a large, steady record of environmental data at Mars (e.g., atmospheric conditions, geological processes, and the radiation environment), all of which are essential to evaluating the modern-day habitability of surface/near-surface environments. These data are necessary to assess ways to preserve any special regions (potential habitats supporting Martian microbial life) in a future era of human exploration.

Despite the existing data record, current observations are insufficient to provide a meaningful understanding of certain environmental factors that likely have long-term impacts on the development (or decay) of Martian habitability. As NASA, other space agencies, and industry leaders advance toward an era of human exploration, MEP can expand environmental knowledge of the Martian system through continued atmospheric and geological observations, as well as provide essential input into models of later phases of the Martian habitability cycle. Additionally, returned samples would increase knowledge about organic chemistry processes on Mars, at global and regional scales and over a range of temporal scales; the nature of any biosignatures; and the relationship between Mars' geological and potential biological history (S1.C). A future mission to search for extant life would investigate locations likely to be present-day refugia for life (e.g., the Martian subsurface). While these missions would greatly expand our knowledge of a potential Martian biosphere, they are but the tip of the iceberg in telling a complete story of life's potential presence or absence on the Red Planet.

MEP is primed to expand the search for life from ancient to extant biology. A key to the search for modern Martian microbial life lies in identifying and exploring refugia (''oases'') where current environmental conditions are hospitable (either episodically or continuously) to life as we know it. These potential special regions (e.g., ice and ice-adjacent locations, subsurface, and high salt environments) are difficult to access and would require significant effort to explore (Figure 11).

Aspects of the Martian environment remain largely unknown and must be understood to establish and informatively update adequate planetary protection and contamination control protocols. Addressing the question of extant life on Mars requires assurance that any detected biosignatures are native to Mars and not transported by human explorers. Incorrectly interpreting signs of present-day life would have a significantly deleterious effect on how to interpret the evolution and likelihood of life there, and more broadly, in the solar system.

Exploring Mars (on Earth) together, research teams pave the way for agile robots and human explorers of the future to search for life in hard-to-reach places below the Martian surface.

Figure 11. Mars analogue expeditions. In a Mars-like cave environment, a team of researchers engaged in Atacama Rover Astrobiology Drilling Studies (ARADS) to test drilling technologies and the ability to detect life below the surface of Earth. *NASA*

2024–2044 SCIENCE THEME 2

S2. SUPPORTING THE HUMAN EXPLORATION OF MARS

Define the high-priority science human explorers would advance at Mars and make observations that synergistically serve both fundamental science goals and Agency objectives for the human exploration of Mars.

S2.A	**DEFINE PRIORITY HUMAN-LED SCIENCE AT MARS** Multidisciplinary community input from science and human-mission-planning disciplines can together articulate the highest value scientific objectives humans could uniquely advance while on the surface and traveling to and from Mars.
S2.B	**CHARACTERIZE POTENTIAL ICE-RICH SITES FOR BOTH ROBOTIC & HUMAN-LED SCIENCE*** The scientific study (with high-resolution imaging and other high-priority science instruments) of candidate ice-rich sites can determine optimal locations for high-priority human-led science, resource potential, and operational feasibility/safety.
S2.C	**STUDY ATMOSPHERIC SCIENCE & WEATHER*** Targeting investigations of the Martian atmosphere/exosphere can support the prediction of extreme events (e.g., dust storms), human-class landing/launch operations, and a better understanding of how terrestrial microbes released during human operations would potentially propagate in the Martian atmosphere.
S2.D	**UNDERSTAND POTENTIAL HEALTH & SAFETY HAZARDS†** Obtaining and characterizing samples can lead to an understanding of mechanical properties (e.g., abrasiveness for suit and hatch seal designs) and breathing hazards to humans (e.g., particle size and potential biological exposures). In support of biological and physical science objectives in the Moon to Mars initiative, MEP can work within SMD and with other Directorates to obtain data on the Martian environment, as identified to be relevant to human-mission planners in assessing ways to protect and strengthen human health and performance.
S2.E	**CONSTRUCT ANALOGUE MISSIONS TO PREPARE FOR EXPEDITIONS TO MARS*** Coordination with other Directorates and international partners to simulate science-driven, robot-assisted expeditions can prepare astronauts and the wider Mars community on Earth for future interplanetary collaboration in making discoveries “in the Martian field” and in transit. Drawing on human lunar activities to feed forward into Mars operational strategies is key.

* Collaborative, dual-purpose: Denotes themes where SMD is not the only Mission Directorate involved.

† Contributing: Denotes themes where SMD has a supporting role to other Mission Directorates.

2.2 SCIENCE THEME 2: SUPPORTING THE HUMAN EXPLORATION OF MARS

For over 25 years, the United States has achieved a continuous robotic presence at Mars and is increasingly poised to establish a sustainable human-robotic future there. A human presence focused on continued scientific discovery would engage the power of human intelligence, agility, and dexterity, accelerating inquiry about possibilities for life and deeper understandings of Mars, Earth, our solar system, and worlds beyond. The coming scale and sophistication of human infrastructure would also enable more powerful laboratories and scientific instruments for real-time studies in transit, in orbit, and on Mars. In collaboration with all NASA Mission Directorates, MEP is committed to advancing a future, sustainable human-robotic presence on Mars, in support of both internal NASA Moon to Mars objectives (M2M, 2023) and community-based recommendations (e.g., OWL, 2023; Mars Architecture Strategy Working Group [MASWG], 2020; International Mars Ice Mapper Measurement Definition Team [I-MIM MDT]; see Appendix C).

Core questions include:

- **What high-priority scientific investigations would be vastly accelerated by human capabilities, aided by robotic companions?**
- **What critical knowledge gaps about the Martian system could robotic missions address to enable human-robotic missions and to protect human explorers?**
- **How can we prepare to maximize precious human time and resources on the Martian surface, in connection with the expert community on Earth?**

Science supporting human exploration provides essential knowledge about:

- key candidate locales that optimally support high-value, scientific investigations; and
- Martian environmental conditions that enable human-mission planners to design and develop infrastructure and technologies for reliability and safety.

Science for human exploration requires a paradigmatic shift among multidisciplinary stakeholder communities who are beneficiaries of the data returned: planetary scientists, astrobiologists, human biological and physical scientists, and experts relying on data for science applications that meet the needs of human explorers, such as ISRU, civil engineering, and in the long-term, agricultural and materials science (e.g., food security, biopolymer production for local manufacturing, and more). With NASA Moon to Mars objectives (M2M, 2023), more unified collaboration among NASA Mission Directorates can maximize both the scientific and cultural value of Mars exploration. Robotic science missions provide a foundation

One of the first steps toward a sustainable human-robotic future is defining scientific goals and objectives worthy of the human endeavor and optimal candidate locations for pursuing it.

of knowledge that can be critical to human-exploration planning and, eventually, real-time decision-making. Current core knowledge gaps relate to Mars resources (water, atmospheric gases, surface materials) and environmental hazards (dust, radiation, toxicity, extreme weather). For science, great progress in answering high-priority investigations can be made through the future availability of high-mass, high-power, human-class infrastructure and the ability for crew to conduct research directly in the Martian field (Figure 12).

Figure 12. Drilling on Mars for science and resources. Artist's concept of future astronauts surveying science site of interest. *NASA*

MEP is committed to supporting the Mars science community in new considerations of what high-priority scientific investigations human explorers would ideally conduct on the surface of

Mars, as well as research on the long journeys from and to Earth (S2.A). Multiple reports have prioritized the search for life as a profound line of inquiry, not only for Mars, but for its implication for life on Earth, in our solar system, and worlds beyond. This focus and other high-priority scientific investigations would drive human expeditions and the selection of candidate sites for the first human home on Mars. Future community studies will inform where, and how, scientific inquiry would most benefit from astronauts' on-site intelligence, ingenuity, and agility, as well as how robotic companions (rovers, helicopter scouts, etc.) would be best equipped to assist them with "super-human" sensing abilities, advance scout work, and access to harder-to-reach or protected locales.

> *In cooperation with other NASA Directorates and international partners, MEP can engage the Mars science community in analogue missions here on Earth that prepare future astronauts for scientific expeditions and research on Mars.*

Such MEP missions must continue to provide key data sets about the Martian environment to inform human-exploration mission designs: scalable and interoperable infrastructure and technologies that enable astronauts to live and work safely on the surface, protection of human health, the wise and sustainable use and reuse of natural resources on Mars, and the preservation of unique features and environments (e.g., any potential ecosystems). In doing so, NASA can shift from a continuous presence at Mars to one that is also sustainable in terms of in situ resource utilization and support from the federal government and other stakeholders.

One of the highest priorities for precursor robotic missions is mapping adequate and accessible near-surface ice (S2.B). Systematic mapping of ice presence (Figure 13) anywhere within a few meters of the surface is key to high-priority investigations related to the search for present life and the history of climatological and geologic change. Water ice as a local resource for human exploration may enable the raw material to be used as propellant for the return trip to Earth, back-up life support, civil engineering (e.g., making concrete, 3D printing structures), and eventually, agriculture.

Multiple reports (M2M, 2023; OWL, 2023; I-MIM MDT, 2022; MASWG, 2020; Keck Institute for Space Studies, Revolutionizing Access to the Mars Surface [KISS RAMS], 2022; etc.) cite a clear gap in the state of knowledge: the location and abundance of near-surface water ice, particularly at low to mid latitudes where human missions are more operationally viable; how deeply buried the water ice is; and the characteristics of the overlying ground (overburden), as relevant to drilling.

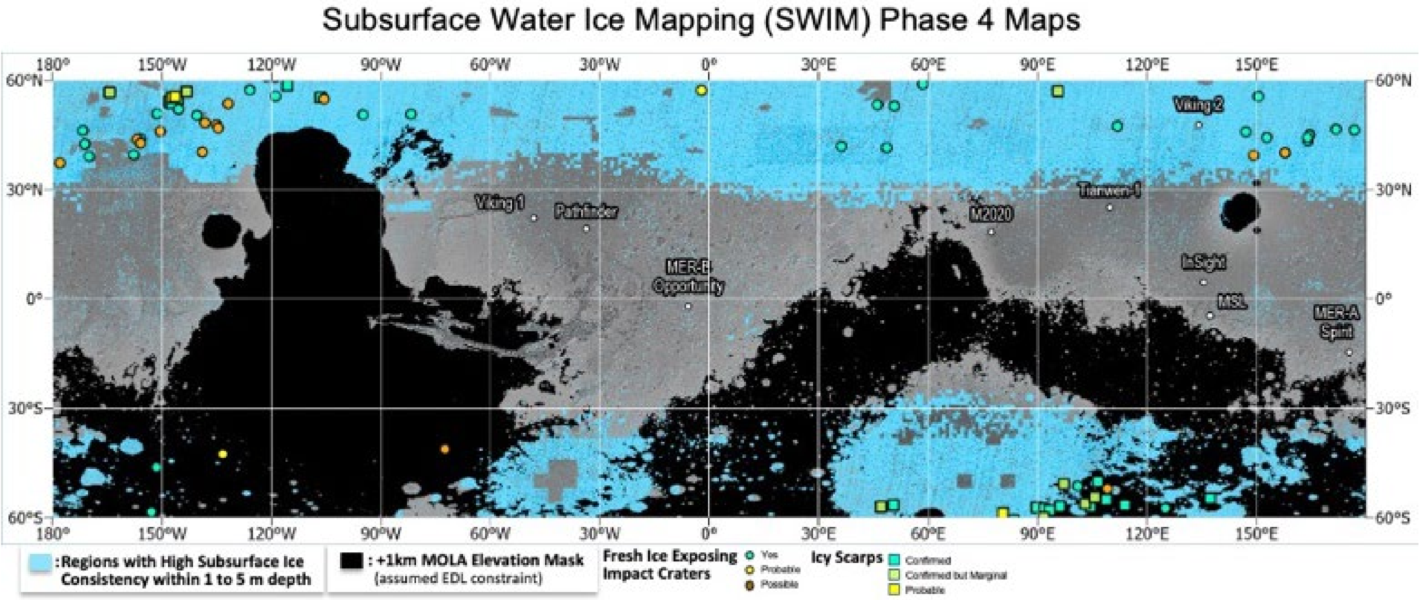


Figure 13. Potential areas with accessible water ice at Martian midlatitudes.
NASA/JPL-Caltech/SWIM

If humans are to explore Mars and conduct scientific investigations safely and affordably, collecting high-priority precursor data about Mars is crucial in the early 2030s for human Mars mission architecture design and risk mitigation, especially given the limited number of Mars launch opportunities (~every 26 months) before anticipated human missions.

Other high priorities are characterizing candidate sites with high-resolution imaging and predicting atmospheric conditions that could impact key events (human-class landings and launch from the surface) and ongoing surface operations (S2.C). Very-high-resolution (<1 m/pixel) images from the High Resolution Imaging Science Experiment (HiRISE) camera on MRO cover only a small percentage of Mars (~5%). HiRISE is a camera capable of taking pictures over vast areas of Martian terrain, and it can do so with a resolution capable of distinguishing features on the scale of about 1 m (about 3 ft). Although virtually all of Mars has been mapped at 5 m/pixel using data from MRO’s Context Camera (CTX), higher resolution is needed to identify hazards (e.g., rocks) and rovers on the surface. MEP does not expect that HiRISE will still be operational beyond 2030 to characterize myriad candidate landing sites for future mission safety and science/resource potential. That is also true for the vertical profiling of atmospheric temperatures and aerosols, as provided by instruments such as those onboard

MAVEN and MRO. While MEP has had continuous weather-monitoring capabilities, significant data gaps related to the drivers of weather (e.g., wind) prevent improved atmospheric modeling that enables weather prediction. That knowledge is particularly important in understanding the frequency and intensity of extreme events such as dust storms and presently unknown clear-air hazards such as wind shear.

The return of Martian samples would assist in characterizing potentially harmful effects of the Martian regolith so that human-mission planners can design mitigation approaches related to human health and to protective equipment and infrastructure (S2.D). Other future remote-sensing investigations could be important to biological and physical science objectives within Moon to Mars objectives (M2M, 2023), requiring close collaboration within SMD and with other Mission Directorates with an expertise in these related scientific disciplines.

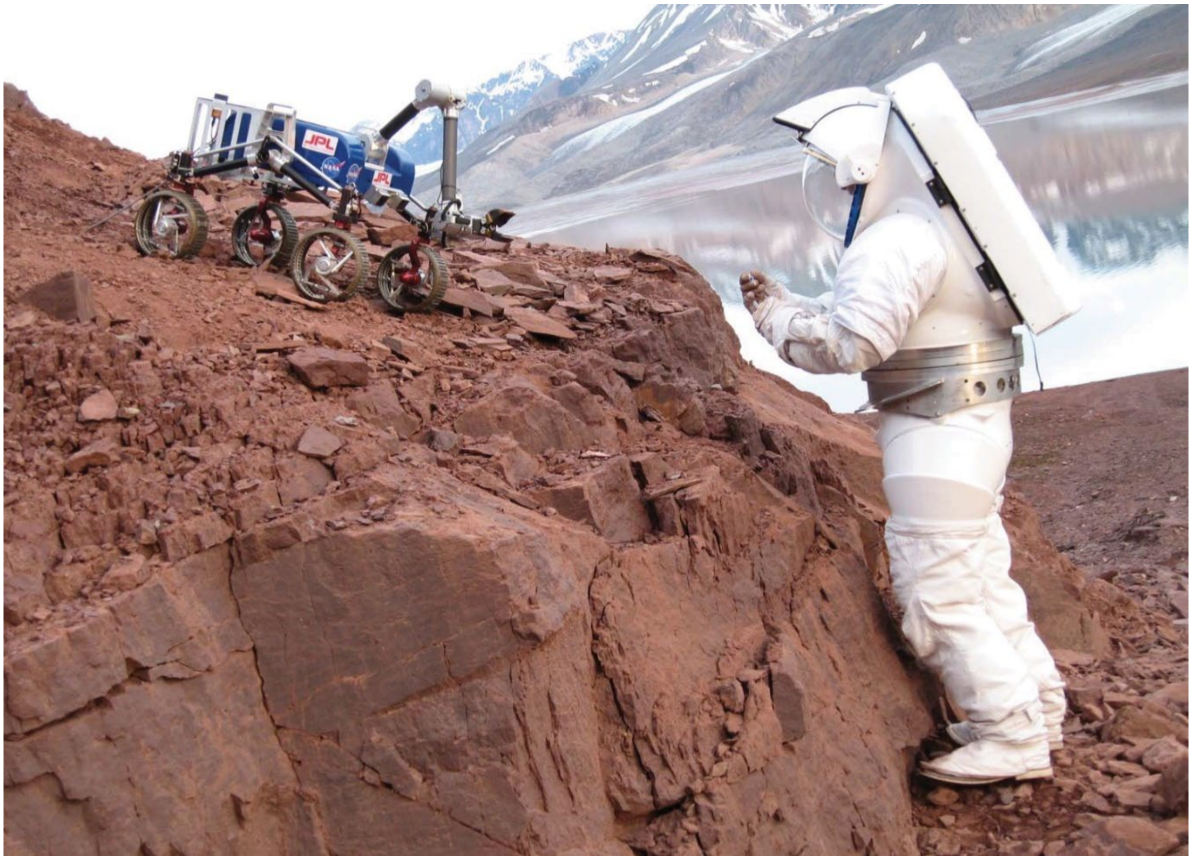


Figure 14. Preparing for human-led, robot-assisted science on Mars, in Mars analogue environments. Vestfonna Geophysical AS, Carnegie Institute of Washington, Norwegian Space Centre, ESA, and NASA collaborated in Artic Mars Analog Svalbard Expeditions (AMASE) to Svaalbard, Norway, where a “cliffbot” tested its mobility, rock-sampling, and life-detection capabilities in highly challenging terrain. *International AMASE Team*

Finally, in near-Mars-like conditions here on Earth, analogue missions (S2.E) (Figure 14) can resolve many open questions about future human-led, robotic scientific operations, such as:

- How would the extreme nature of the Martian environment affect the way in which astronauts conduct scientific research during Mars walks?
- How can the Mars science community prepare and guide astronauts in conducting scientific expeditions and research on Mars, especially given delays in communication between Earth and Mars and the realities of crew autonomy?

Missions to Mars–analogue environments on Earth would allow mission planners to answer such questions by testing solutions for known problems; encountering and addressing previously unknown issues that emerge; and improving hardware, software, and human factors in ways that vitally support mission success.

In cooperation with other NASA Directorates and international partners, MEP can engage the Mars science community in analogue missions here on Earth that prepare future astronauts for scientific expeditions and research on Mars.

In this plan, high-priority, science-enabling investments serving both robotic and human exploration include:

- high-resolution imaging to enable not only the characterization of physical surface processes and changes in seasonal landscapes, but also the selection of optimal sites for robotic and human exploration, in situ resource needs, and engineering constraints;
- telecommunication and navigation advances, in coordination with NASA's SOMD and Space Communications and Navigation (SCaN) program, that return orders-of-magnitude greater data volume, enabling the mapping of Mars at resolutions comparable to our mapping of Earth, while providing new positioning, navigation, and timing (PNT) services to accommodate the needs of advanced robotic systems and, ultimately, humans on Mars; and
- global weather instrumentation for monitoring, modeling, and forecasting (especially extreme events such as dust storms) to support safe landings, surface operations (including planned scientific investigations), and launches from the Martian surface through the development of risk-mitigation strategies.

2024–2044 SCIENCE THEME 3

S3. REVEALING MARS AS A DYNAMIC PLANETARY SYSTEM

Understand the dynamic geological and climatological processes on Mars to illuminate the evolution of the Martian system, our home planet Earth, our solar system, and distant planets around other stars.

S3.A UNDERSTAND MARS AS A SYSTEM THROUGH INVESTIGATIONS OF THE GLOBAL ENVIRONMENT

These investigations illuminate the ways in which individual components of the Martian global environment—the atmosphere, hydrosphere, cryosphere, and geosphere—interact to make up the Martian system.

S3.B INVESTIGATE ANCIENT & MODERN DRIVERS OF CHANGE ON VARIOUS TIMESCALES

Investigations of the dynamic processes that drive changes on timescales ranging from seconds to eons over a diverse range of local environments enable a shift from monitoring change to predicting it and testing theories about planetary processes that extend to Earth and other worlds.

S3.B-1 Planetary Evolution

Geologic Change from Early Mars through the Present.

S3.B-2 Early Environmental Change

Early Environmental Change through the Stratigraphic Record

S3.B-3 Recent Climate Evolution

Recent Climate Evolution through the Study of Volatile Cycles

S3.B-4 Dynamic Modern Environments

Dynamic Modern Environments and Their Processes

S3.B-5 Modern Habitability

Characterization of Diverse Environments and Their Potential to Be Habitable

S3.C EXPLORING THE POSSIBILITIES FOR “GOLDILOCKS” WORLDS

Mars uniquely retains a history of planetary evolution in its geological record, one that has been erased on Earth due to its own more complex, dynamic systems. Mars thus holds significant clues about the reasons some planets develop conditions that are “just right” for life (i.e., Goldilocks conditions). When compared to knowledge about our home planet, findings on Mars can have a profound impact on comparative planetary and astrobiology research for this solar system and those around other stars.

2.3 SCIENCE THEME 3: REVEALING MARS AS A DYNAMIC PLANETARY SYSTEM

When we see images of Mars, we can immediately recognize it as a close relative of Earth. Though alike in many respects, fundamental differences are both fascinating and challenging to understand. Ever-changing throughout its recent and ancient history, Mars is a diverse planet (Figure 15), but unlike Earth, it lacks a pervasive biosphere, plate tectonics, or vast expanses of open water at the surface. With similar, but much simpler, interacting elements compared to Earth, Mars is the most accessible place to test theories about planetary evolution and atmospheric circulation, as well as habitability in our solar system and beyond. Erosion by water and plate tectonics has destroyed the earliest record of Earth's surface environment. Mars, however, retains a unique and substantial record of the earliest period of its formation under evolutionary conditions similar to Earth's, as well as later evolutionary processes. Together, these records help resolve which evolutionary pathway Mars followed in its history (e.g., as depicted in Figure 10).

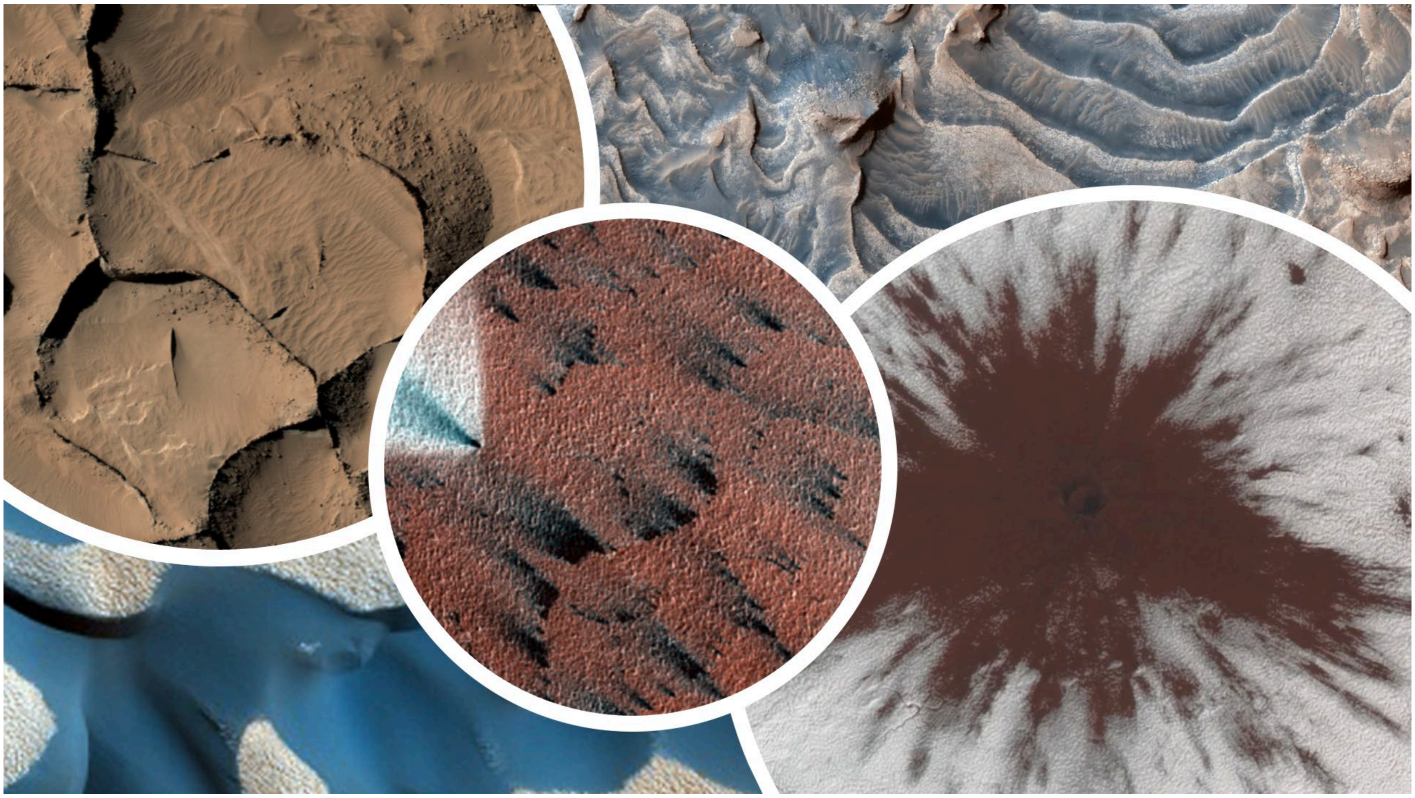


Figure 15. Examples of the diversity of terrain on Mars. *NASA/JPL-Caltech/UArizona*

What if we could affordably explore the tremendous diversity of surface features on Mars and the ancient and modern changes on Mars they reveal?

A higher cadence of lower-cost missions that can land in more of the most scientifically compelling places and supported by constellations of orbiters capable of continual planetwide observations and high-volume data return is essential to studying Mars the way we study Earth.

This preservation of physical evidence of the earliest planetary environments is unmatched in the solar system. Despite the impressive global coverage of the surface and atmosphere achieved by past and current Mars missions, NASA has only explored a small fraction of these environments in detail, generating many questions about how representative these limited locations may be. What is observed from Martian orbit does not always perfectly align with finer details detected on the Martian surface. Determining what processes are occurring at finer scales and in unexplored locations is imperative to understanding the whole complex, interacting system. Along with depths of the Martian subsurface, unexplored places on Mars include the ancient southern highlands and parts of the polar regions, which together comprise nearly 2/3 of the Martian surface.

Key questions include:

- **What can the diversity of places on Mars reveal about the evolution of Mars compared to Earth and other planets?**
- **How do changes in key components of the Martian climate system (water, carbon dioxide, dust) affect Mars’ climate evolution and its impact on the solid surface?**
- **Where are indicators of geologically recent climate-change events preserved in accessible near-surface and surface ice?**
- **How does the distribution, structure, and activity of surface and near-surface ice affect weather, climate, and geologic processes and how might that suggest candidate robotic and human landing sites?**

As on Earth, the Martian atmosphere, surface, and subsurface are tightly coupled (Figure 16). Volatiles such as water and carbon dioxide pass among them, playing key roles in both ancient and modern processes. However, the differences between the two planets provide an avenue for more rigorous tests of theories about the physics of planetary processes and the potential for habitable environments. Investigations addressing these key questions illuminate the ways in which individual components of the Martian global environment—the atmosphere, hydrosphere, cryosphere, and geosphere—are integrated to make up the Martian system (S3.A).

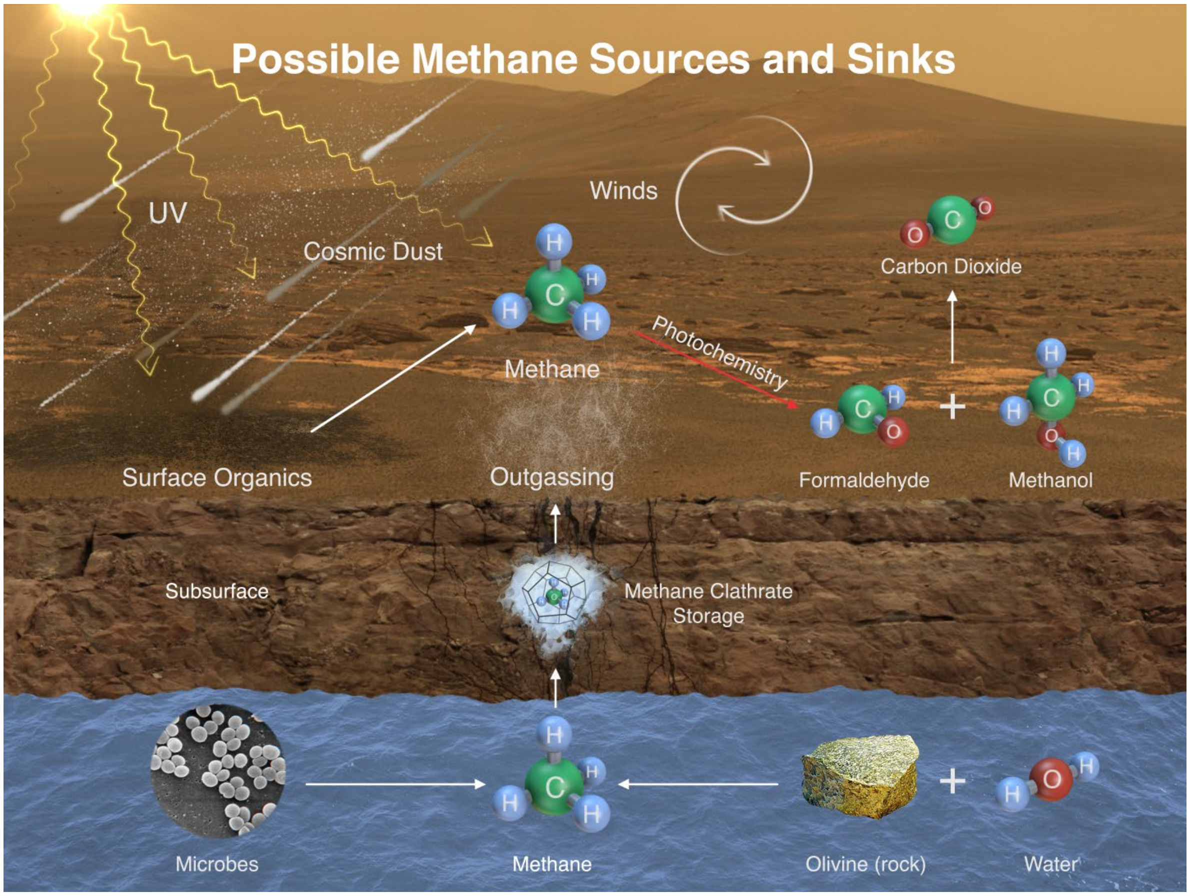


Figure 16. Potential for system science. Studying Mars as a set of systems can resolve open questions about Mars, such as the biological or abiological source(s) of methane. *NASA/JPL-Caltech/SAM-GSFC/Univ. of Michigan*

As much as we have learned about Mars, the next revolution in understanding will come from viewing Mars as a counterpoint to Earth, spanning the atmosphere, geosphere (including the cryosphere/hydrosphere), potential biosphere, and interactions among them through time.

By comparing Martian systems and their interactions to those of Earth and other planets, NASA has the opportunity to make significant gains in understanding the atmosphere, geosphere, cryosphere, and potential biosphere:

Atmosphere. Long an aspiration of the Mars community, short- and possibly long-term weather prediction would be enabled by the availability of wind and other coordinated measurements providing information about atmospheric circulation. Atmospheric dust storms have seasonal and spatial triggers that lead to an elevated dustiness of the Martian atmosphere. What drives the growth of planet-encircling dust events, observed only periodically, remains unknown. Understanding drivers of extreme weather would significantly mitigate risks for both robotic and future human operations. Processes driving Mars climate evolution also appear widespread in our solar system and undoubtedly beyond. For example, other bodies (e.g., Triton, Pluto, Titan) have major atmospheric constituents that condense to modify the surface. However, these destinations remain challenging worlds to observe in detail given their distance. Using Mars as the archetype helps test models of planetary processes and contributing factors (e.g., a planet’s radiative balance, its orbital tilt, and the availability of volatiles).

Geosphere. Geophysical investigations of the deep mantle and core can indicate the state of the Martian interior, providing information about when Mars cooled and when its global magnetic field turned off. That understanding informs the timing of major transitions in the Martian environment. Investigating the structure of the Martian crust and lithosphere, along with changes in it, can illuminate why the northern and southern hemispheres of Mars are so different. The history of bombardment is recorded in its highly cratered surface, as is the extent of modern volcanic and tectonic activity. Early Mars went through dramatic environmental transitions, from a “warm and wet” phase, when liquid water was seemingly widespread and abundant, to a much drier phase, as evidenced by the stark transition in surface mineralogy found in younger terrains. Determining if early Mars had a large ocean in the northern hemisphere would reveal the abundance of water in the Martian system at that time, touching on questions of habitability, volatile loss, and surface chemistry. Shallow measurements of surface heat flux and vapor exchange address both climate evolution and Mars’ interior

Figure 17. Thick sheet of exposed water ice on Mars. An icy cliff face on Mars indicates that near-surface water ice may exist widely throughout the Martian mid-latitudes. *NASA/JPL-Caltech/UArizona*

structure. On the surface, active changes such as the cryptic darkened streaks that seasonally appear on the walls of some craters and other slopes (recurring slope lineae) lack a definitive origin to explain their repetitive behavior year after year. Continuous global observations can address such mysteries.

Cryosphere. The cryosphere is an archive of past climate states on Mars, serving as a “time machine” that enables the reconstruction of the Martian climate over millions of years. Polar deposits preserve evidence about the global environment (temperature, chemistry, orbital state, aerosol content, etc.) at the time of their emplacement and provide a record of the water content of the Martian surface. Regions closer to the equator preserve, at greater depth, ice deposits emplaced hundreds of thousands or millions of years ago, offering a complementary view of the past Martian climate. The extent to which these deposits are in disequilibrium with the current environment offers clues to the composition of the near-surface regolith and the rate of vapor exchange with the atmosphere. These preserved near-surface reservoirs (e.g., Figure 17) are within, or very near, our current capability to explore, and represent some of the most exciting environments in which to demonstrate new technologies for landing, mobility, and cold-temperature operations.

Potential Biosphere. If Mars has life today, biogeochemical processes may be taking place and shaping the planet, but these processes may be happening at rates and scales not yet definitively detected. For instance, detected seasonal methane fluxes could be caused by either geologic or biologic processes. Any microbial life on Mars could be similar to life as we know it here on Earth. Alternatively, life might have formed and evolved differently given unique initial and transformative environmental conditions occurring throughout Martian history. Along with observations from orbit and on the surface of Mars, studies of extremophiles in Mars analogue environments on Earth can provide insights into the possibilities for Martian life and its adaptations.

The Systems Approach

While this MEP 2024–2044 Plan largely builds on gathering a wealth of individual, institutional, national, and international talent to enable Mars exploration and share in its benefits, these underlying concepts are particularly resonant in this holistic approach to studying Mars as a dynamic system. It will likely take many partners and many coordinated, ongoing observations and investigations to be able to approach studying Mars systemically the way we study Earth, albeit at a smaller scale. While inherently broad, the intent of this theme is not to "do everything" in the next 20 years, but rather to provide the scientific community with considerable flexibility in prioritizing investigations, responding to discoveries, and finding solutions of greater cross-disciplinary benefit.

Exploring Mars as a system enables deeper investigations into the ancient and modern drivers of change. These investigations go beyond observing what has occurred or is occurring to exploring the *Why?* and the *How?* Dynamic processes that drive changes on timescales ranging from seconds to eons over a diverse range of local environments. Investigations are needed that enable a shift from monitoring change to predicting it, while testing theories about planetary processes that extend to Earth and other worlds in our solar system and beyond (S3.B). This theme adopts community-defined sub-themes, as derived from the work of the Mars Concurrent Exploration Science Analysis Group (MCE-SAG, 2023):

Planetary Evolution. Studying the evolution of Mars throughout its history contributes to understanding how rocky worlds in our solar system and in exoplanetary systems develop. Such developments are shaped by typical exogenous events (e.g., impact cratering) and endogenous geologic and atmospheric processes that influenced the evolution of the Martian crust and interior. Knowledge gaps include understanding why the northern and southern hemispheres of Mars are so markedly different, when the Martian core stopped generating a global magnetic field, and the chronology of heavy to light bombardment seen in the sizes and distribution of craters and other surface characteristics.

Early Environmental Change. Studying early environmental change through the stratigraphic record would address unanswered questions about this early time in Martian history when conditions on Earth and Mars were similar, with environments conducive to early microbial life. Mars missions have not yet explored some of the most ancient features and surrounding environments on Mars, so a number of research gaps remain. These include whether early Mars had oceans; what early atmospheric conditions were like; when, where, and how long liquid water existed in specific places on Mars; when and how environmental changes took place; and how and when conditions on Mars diverged from those on Earth.

Recent Climate Evolution. Using ice records and atmospheric profiles, the study of volatiles cycles is extremely important in understanding recent climate change on Mars. Volatiles include water and other chemicals / chemical compounds that undergo phase changes (e.g., carbon dioxide and trace gases such as methane). Much of the water on Mars lies below its surface in the form of ice, as liquid water is not stable on its surface. It is currently unknown how far buried ice extends to the equator and how near to the surface it may be at different latitudes. Also unknown is a more complete understanding of the layers, including those at the poles. These polar layers hold many clues to the planet's climate history. Along with other atmospheric processes, seasonal exchanges of volatiles among the near surface, surface, and atmosphere play a large role in weather and recent climatologic changes, as well as in atmospheric loss. Mission data are currently incomplete on the processes that deposit and transport ice, and whether liquid water in some near-surface and surface environments might be possible, as relevant to habitability and the potential for life.

Dynamic Modern Environments. The Martian surface is always changing (Figure 15), as visible in ice patterns, avalanches, subtle shifts in dunes, recurring slope lineae, new impacts (including those exposing near-surface ice), and dust-lifting activities ranging from dust devils to regional and even global dust storms. Less visible are other important geochemical changes related to both planetary and atmospheric processes. Characterizing weather and other dynamic atmospheric processes can reveal processes responsible for many changes on the surface, and the ability for continuous, long-term monitoring can capture both interactions and changes through time.

Observations of modern-day processes (e.g., weather, tectonics, solar-wind interactions) have applications for both robotic and human missions. For example, the ability to monitor and predict weather is relevant to both robotic and human operations, particularly for extreme events such as global dust storms. Characterizing the environment in which human explorers would live, work, and study can significantly reduce risk and extend the scientific return of both robotic and human missions.

Modern Habitability. Future missions would be able to study the potential range of viable modern-day habitats existing on Mars, including near-surface briny deposits, water-ice deposits, cave environments, and even potential aquifers that might exist deep beneath the surface. Exploring these harder-to-reach potential “oases for life” would require new and novel approaches to access them and to handle samples from them.

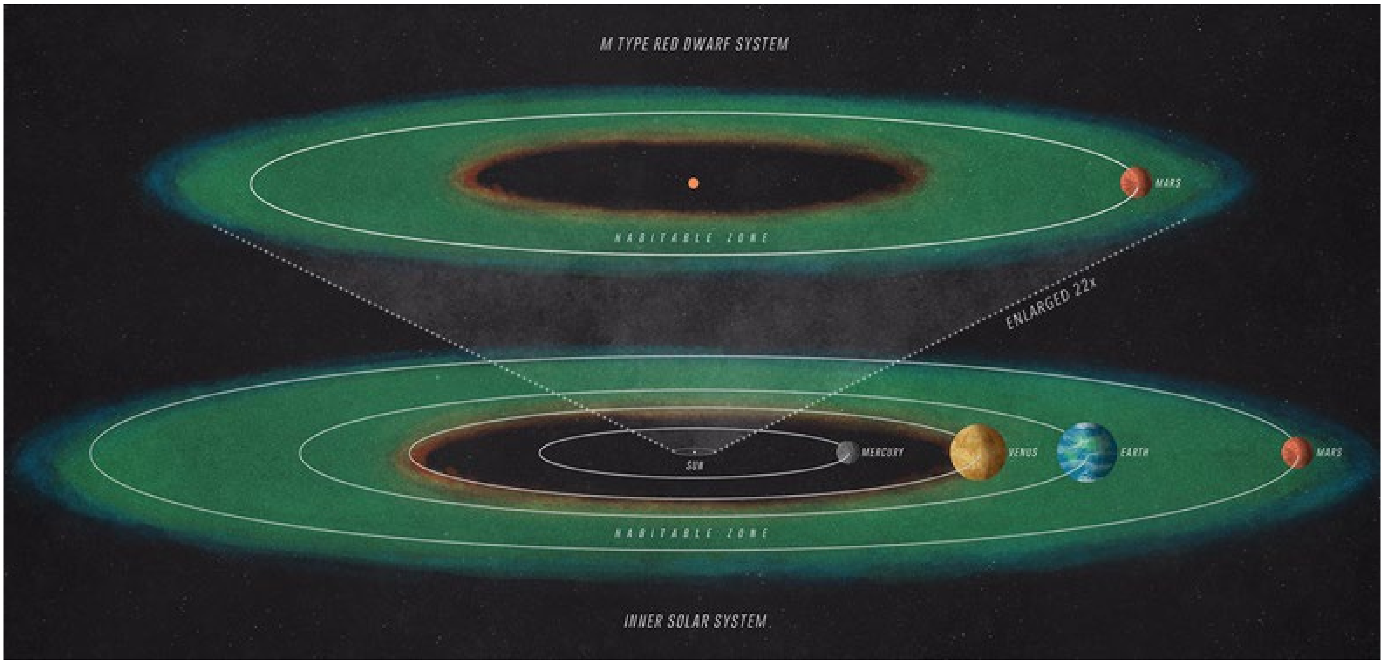


Figure 18. Artist’s concept of the habitable zone. Through comparisons of Mars, Earth, and Venus in our solar system, scientists can gain a better understanding of habitable conditions elsewhere. *NASA/GSFC*

Over the past two decades, MEP missions have successfully determined that Mars has had habitable conditions (episodic presence of liquid water for sufficient durations and organics, the chemical building blocks of life as we know it). With that knowledge, Mars missions are transitioning toward seeking life itself. On Earth, many environments extreme to humans are hospitable to many organisms with very different types of metabolism and other life processes. Understanding the range of environments conducive to life on both Mars and Earth can ground our understanding of what makes a habitable world—in our solar system and elsewhere (Figure 18). Through comparative planetology, MEP can contribute to crosscutting topics in solar-system science and astrobiology.

Revealing Mars as a “goldilocks world” (a planet within the habitable zone where conditions may be just right for supporting life) can advance our fundamental understanding about the potential for life on rocky worlds orbiting other stars.

> ***What if we could study Mars the way we study Earth****—as a dynamic system with a growing network of complementary, replenishable science instruments providing more continuous global coverage, plugged into lower-cost NASA and commercial satellites with standardized interfaces?*

To achieve a more holistic understanding of Mars as an active planet, MEP is poised for a whole new era of exploration based on its past accomplishments at Mars, the growing industry, and other capabilities. Taking a systems view—seeing Mars as a whole—depends on studying Mars the way we study Earth. Here on our home world, vast networks of spacecraft continually acquire complementary and often coordinated data on the ground, in the air, and from orbit. The challenge for Mars is how to enable such research in an affordable way, gradually providing the depth and breadth we have for the Earth system. The value is clear. Per multiple community reports (KISS RAMS, 2022; MASWG, 2020; OWL, 2023), studying Mars as a *system* enables greater insight into the timing and sequence of environmental transitions, both ancient and modern. “Systems science” is essential to a deeper understanding of planets and moons in our solar system, as well as worlds around other stars.

MEP seeks opportunities to utilize lower-cost missions that can gather data across broader and more diverse targets on Mars. Eventually, greater numbers of affordable missions sent more frequently can, together, provide greater coverage of Mars and coordinated observations across time and geographical points of interest. Maintaining a consistent observational record of the Martian system is also an extremely valuable pursuit requiring repeat measurements over different temporal and spatial scales to make connections between the physical drivers of change and the planet’s response to them.

Eventually, building networks of complementary orbital and surface observations (Figure 19) would link MEP’s past 20 years of surface imaging and atmospheric monitoring with new opportunities to understand the drivers of change, leading to an emerging ability to predict change and to simulate better ancient processes with modern data. Investigating dynamic processes that drive changes on timescales ranging from seconds to eons over a diverse range of local environments offers a glimpse into what the rest of the solar system may hold in store. It tests theories and models that scientists can extend to other worlds in our cosmic neighborhood and beyond. Understanding active changes can also significantly reduce the costs and risks to future robotic and human missions, providing context for science they would conduct and enabling engineers to mitigate threats to safety and success.

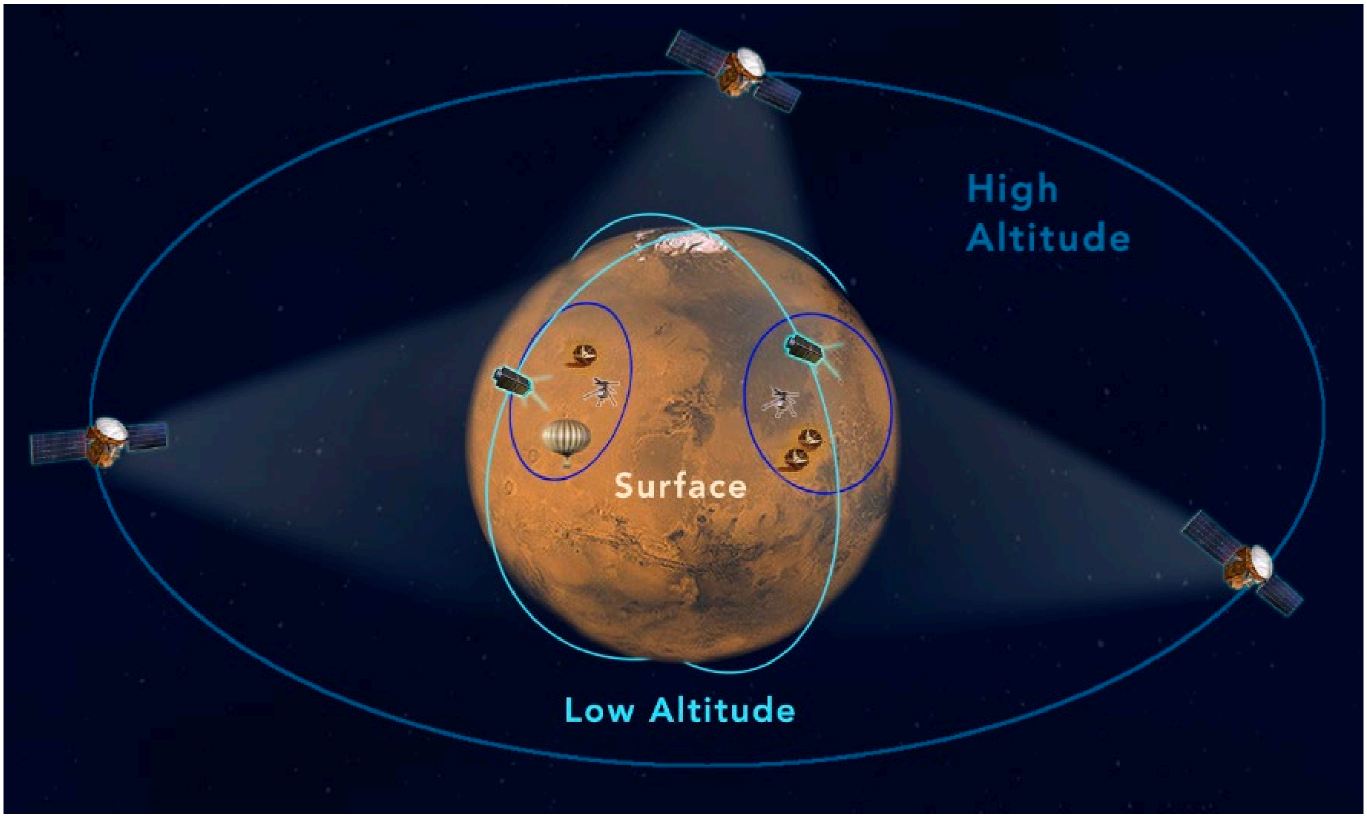


Figure 19. Mars networks supporting Mars systems science. Studying Mars as a system of systems can resolve many open questions about Mars. *NASA/JPL-Caltech*

2.4 INTERCONNECTIONS AMONG THE 2024–2044 SCIENCE THEMES

To maximize scientific discovery and the nation's return on investment in Mars exploration, careful execution of the MEP 2024–2044 Plan can leverage mission investigations to benefit multiple science themes. The three co-equal science themes (Exploring the Potential for Martian Life, Supporting the Human Exploration of Mars, and Revealing Mars as a Dynamic Planetary System) do not exist in isolation; many of the most significant scientific discoveries can, and will, come from areas where disciplines overlap.

> *Seeking scientific synergies—particularly where all three science themes are served—can maximize the nation's return on investment in Mars exploration.*

S1 and S2: Potential Martian Life & Human Exploration

If any life on Mars exists today, it has likely sought refuge in locations isolated from the intense radiation, dramatic temperature swings, and general absence of water across much of the surface. Seeking evidence of modern microbial life may require accessing the subsurface at depths of several tens of meters or lower, where conditions are more favorable to life. That presents challenges to robotic drilling systems and would likely require the assistance or direction of humans on the surface. Such activities are ideally suited for human exploration, as the mobility and dexterity of humans to operate a drill, collect samples of ice and other volatiles, and analyze them in situ with advanced instrumentation exceed that of current robotic systems. Investigations of caves and other unique areas where life may be found would benefit from a human presence to command companion robots (either directly or telerobotically) to explore areas too risky or inaccessible for humans. Characterizing potential sites on Mars where the subsurface is accessible for both astrobiology and human activity can benefit these themes.

S1 and S3: Potential Martian Life & Mars as a Dynamic Planetary System

Both themes view Mars as a holistic system, with interacting parts in constant communication. How do these components interact, and how does this interaction change with time? Does Mars have a biosphere that affects, and is affected by, these changes? Discovery of present (or even past) life would be a dramatic finding by itself, but equally significant would be an understanding of the environment that enabled life to take hold and (potentially) endure. For example, the slow evolution of Mars' orbital state greatly alters the near-surface cryosphere by redistributing water ice between the poles and lower latitudes. Given that water is essential for sustaining life, the geographic pattern of habitable regions evolves with time. Comparing the evolution of Mars and Earth offers a way to reveal the different drivers of change.

S2 and S3: Human Exploration & Mars as a Dynamic Planetary System

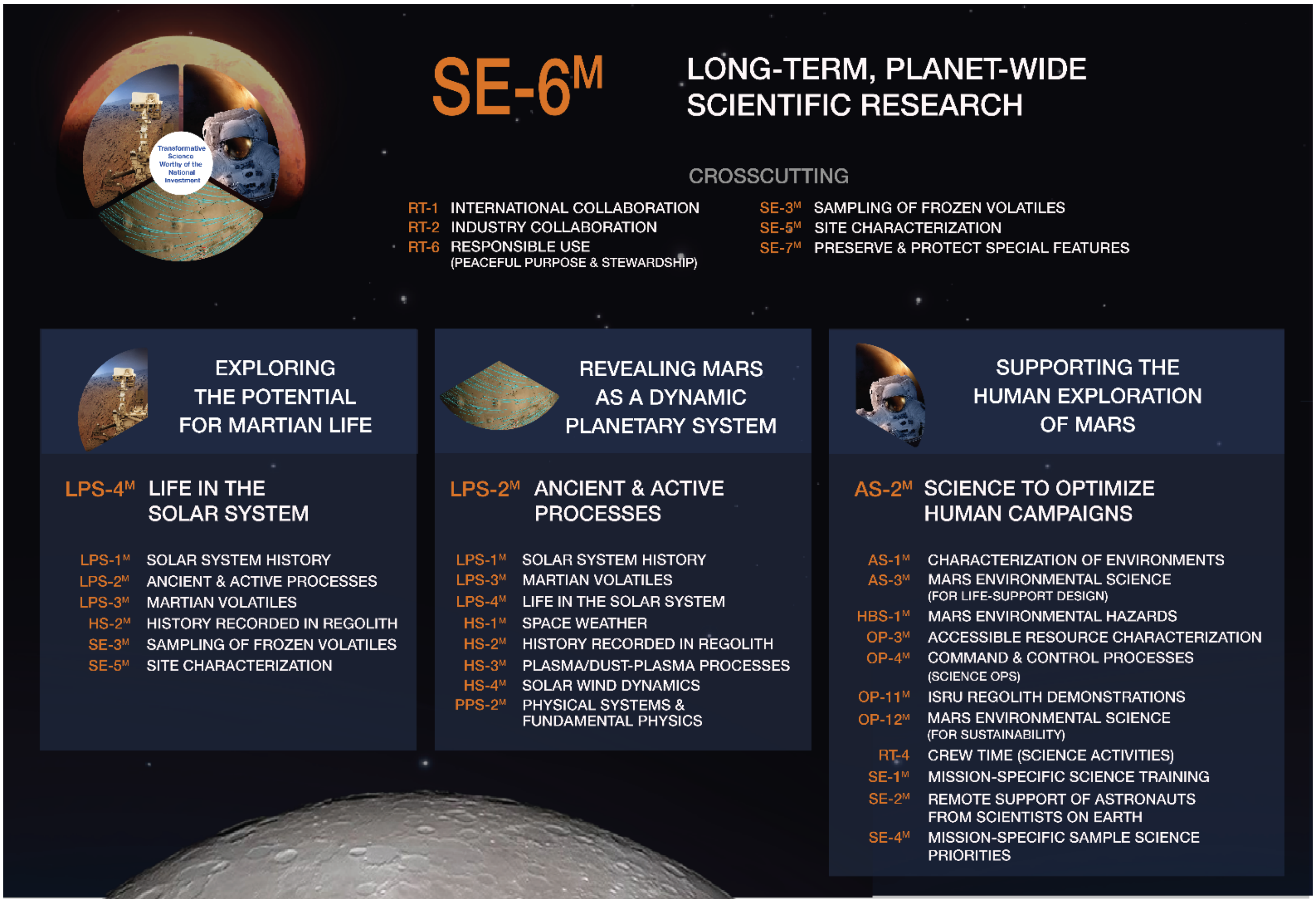
Mars is constantly evolving, including on timescales observable by humans. Understanding Mars' rapid variations in weather and the dust environment are among the areas deemed essential for reducing the risks (both material and in terms of operational efficiency) to humans on the surface and for pursuing studies of comparative planetology—how and why Earth, Mars, and other planets differ.

One valuable element of the human exploration of Mars is the ability to establish a scientific infrastructure designed to endure longer than a single mission. For example, locating and assembling meteorological towers to obtain environmental information in the near-surface atmosphere may be an activity for astronauts to pursue as a means of studying the dynamic modern Martian environment, including the radiation field, dust lofting and settling, and wind. In alignment with guiding documents (OWL, 2023; M2M, 2023), such activities could achieve decadal-class science, while optimizing crew safety and surface operations.

The greater ease with which humans can identify, process, and obtain samples is another distinct advantage of human exploration, and may be a driving factor in the first several crewed missions to Mars, based on guiding documents (OWL, 2023; M2M, 2023). High-priority science objectives established at the first landing sites would likely seek to engage humans in exploring regions that reflect the temporal evolution of the planet. Understanding environmental change through analysis of the local stratigraphic record is an element of Science Theme 3 and likewise might serve as a core aspect of scientific investigations pursued by human explorers.

Interconnections and Continuity Among All Three Science Themes

At the nexus are topics that interconnect all three science themes. One example is the study of modern-day habitability. Distinct from the search for life, habitability science focuses on elements of the environment necessary for the sustenance of life, irrespective of whether it ever took hold. These elements include a moderate, clement environment; an energy source; chemicals necessary for life; and the presence of liquid water. Another related example is in the field of ice science. Areas with near-surface ice serve as places with a higher potential for Martian life, potentially provide necessary and accessible water-ice resources for human explorers, and play a key contributory role in the Martian hydrologic cycle. Measuring the extent and vertical profile of these reservoirs can speak volumes about recent climate evolution on Mars, as surface deposits wax and wane differently across different surface locations. To the extent that life-seeking robotic and human missions might explore locations conducive to present-day life (i.e., close to a water source and isolated from the surface environment), such an investigation would address all themes.



SE-6^{M} LONG-TERM, PLANET-WIDE SCIENTIFIC RESEARCH

CROSSCUTTING

RT-1	INTERNATIONAL COLLABORATION	SE-3^{M}	SAMPLING OF FROZEN VOLATILES
RT-2	INDUSTRY COLLABORATION	SE-5^{M}	SITE CHARACTERIZATION
RT-6	RESPONSIBLE USE (PEACEFUL PURPOSE & STEWARDSHIP)	SE-7^{M}	PRESERVE & PROTECT SPECIAL FEATURES

EXPLORING THE POTENTIAL FOR MARTIAN LIFE

LPS-4^{M} LIFE IN THE SOLAR SYSTEM

LPS-1^{M}	SOLAR SYSTEM HISTORY
LPS-2^{M}	ANCIENT & ACTIVE PROCESSES
LPS-3^{M}	MARTIAN VOLATILES
HS-2^{M}	HISTORY RECORDED IN REGOLITH
SE-3^{M}	SAMPLING OF FROZEN VOLATILES
SE-5^{M}	SITE CHARACTERIZATION

REVEALING MARS AS A DYNAMIC PLANETARY SYSTEM

LPS-2^{M} ANCIENT & ACTIVE PROCESSES

LPS-1^{M}	SOLAR SYSTEM HISTORY
LPS-3^{M}	MARTIAN VOLATILES
LPS-4^{M}	LIFE IN THE SOLAR SYSTEM
HS-1^{M}	SPACE WEATHER
HS-2^{M}	HISTORY RECORDED IN REGOLITH
HS-3^{M}	PLASMA/DUST-PLASMA PROCESSES
HS-4^{M}	SOLAR WIND DYNAMICS
PPS-2^{M}	PHYSICAL SYSTEMS & FUNDAMENTAL PHYSICS

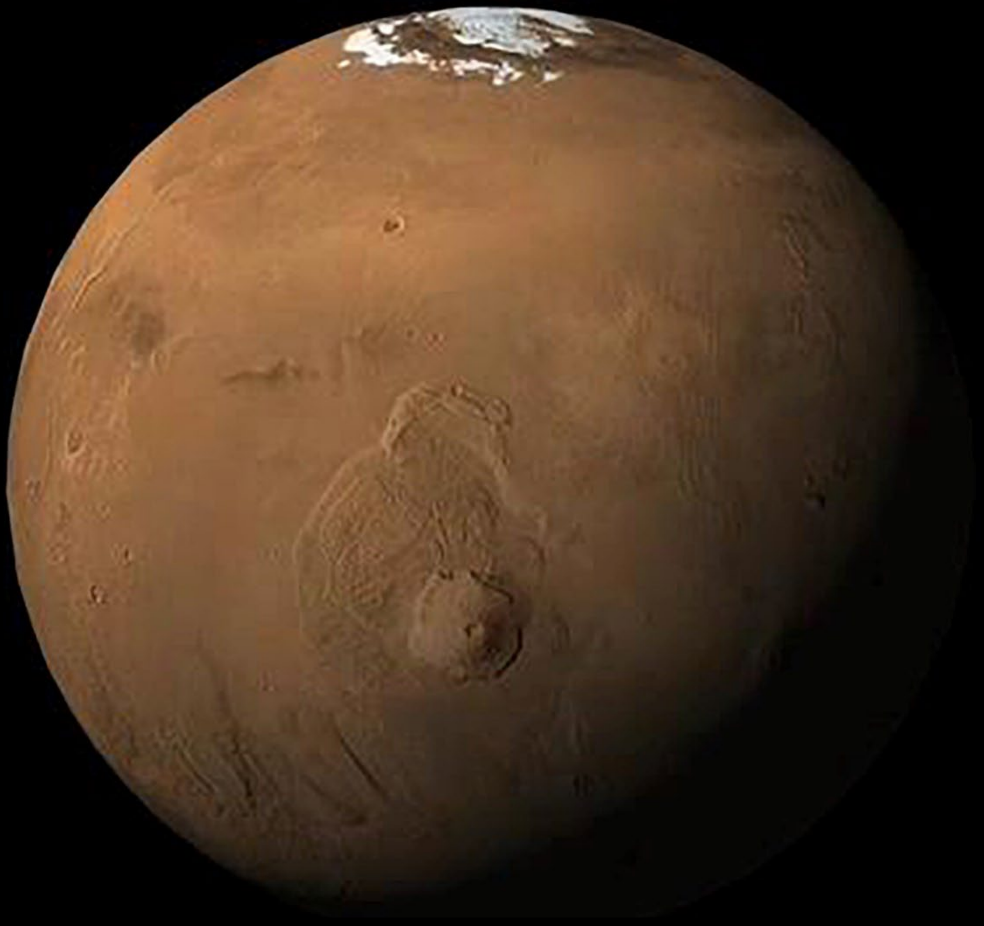
SUPPORTING THE HUMAN EXPLORATION OF MARS

AS-2^{M} SCIENCE TO OPTIMIZE HUMAN CAMPAIGNS

AS-1^{M}	CHARACTERIZATION OF ENVIRONMENTS
AS-3^{M}	MARS ENVIRONMENTAL SCIENCE (FOR LIFE-SUPPORT DESIGN)
HBS-1^{M}	MARS ENVIRONMENTAL HAZARDS
OP-3^{M}	ACCESSIBLE RESOURCE CHARACTERIZATION
OP-4^{M}	COMMAND & CONTROL PROCESSES (SCIENCE OPS)
OP-11^{M}	ISRU REGOLITH DEMONSTRATIONS
OP-12^{M}	MARS ENVIRONMENTAL SCIENCE (FOR SUSTAINABILITY)
RT-4	CREW TIME (SCIENCE ACTIVITIES)
SE-1^{M}	MISSION-SPECIFIC SCIENCE TRAINING
SE-2^{M}	REMOTE SUPPORT OF ASTRONAUTS FROM SCIENTISTS ON EARTH
SE-4^{M}	MISSION-SPECIFIC SAMPLE SCIENCE PRIORITIES

Figure 20. Alignments between MEP 2024–2044 science themes and M2M Objectives. The signature MEP contribution to M2M Objectives is long-term, planet-wide, scientific research. Other M2M science-related objectives are correlated with the three MEP science themes in this plan. Highlighted in larger font are the objectives that most closely match each theme, with some key related and supporting objectives below. Note that the intent is to provide a high-level view, not to suggest that the cited objectives belong only in the places listed, as cases can be made for other alignments depending on mission-specific investigations. As for the MEP themes, the M2M Objectives often overlap. Identifying and developing synergies among and between the MEP themes and M2M Objectives can maximize discovery. *NASA/MEP*.

Along with the four initiatives described in this plan (see Sections 3.1–3.4), MEP is committed to executing its Program of Record: operating missions, multi-mission operations, research, contributions to international partnerships, and significant roles in the MSR campaign (Figure 20), which consists of Mars rover Perseverance (i.e., Mars 2020) and the Sample Receiving Project (SRP).



3

PROGRAM OF RECORD AND NEW PROGRAM INITIATIVES

Program of Record: Operating Missions

> Accomplish the highest priority scientific investigations of MEP operating missions to ensure the greatest return on investment for the nation.

Currently operating NASA Mars missions include:

2001 Mars Odyssey (ODY): An orbiter that launched in 2001, ODY created the first global map of chemical elements and minerals that make up the Martian surface. The orbiter's telecommunications systems provide a crucial service for Martian spacecraft.

Mars Reconnaissance Orbiter (MRO): An orbiter that launched in 2005, MRO conducts climate studies, probes the subsurface, and analyzes surface-modifying processes, including evidence that liquid water episodically persisted on the surface of Mars long enough to provide habitable conditions. The orbiter's telecommunications systems provide a crucial service for other Martian spacecraft.

Mars Atmosphere and Volatile EvolutioN (MAVEN): An orbiter that launched in 2013, MAVEN is the first mission devoted to understanding the Martian upper atmosphere.

Mars Science Laboratory (MSL) (Curiosity rover): A rover that launched in 2011, *Curiosity* set out to determine whether Mars ever had the right conditions to support life and has found chemical and physical evidence of past habitable environments on Mars.

Mars 2020 (Perseverance rover): A rover that launched in 2020, *Perseverance* seeks signs of ancient microbial life and collects samples of rock and regolith for possible Earth return.

These missions are highly successful, all operating well beyond their anticipated lifetimes. To the greatest extent possible, MEP will support high-priority investigations of existing Mars science missions in its Program of Record, consistent with its budget and with regular evaluation through the periodic Planetary Mission Senior Review, while balancing those investments with the community's equal desire for new science and new competitive opportunities. New Mars mission priorities are informed by decadal survey recommendations (OWL, 2023), MEP goals (MEPAG, 2020) and related community studies, and Agency-level priorities such as NASA's Moon to Mars objectives (M2M, 2023).

Program of Record: Multi-Mission Operations

> Enable scientific investigation utilizing the Mars Relay Network (MRN), a multi-mission operations effort that coordinates the combined NASA and ESA orbiter capabilities to transfer data to and from Mars surface missions.

The MRN leverages the combined NASA and ESA orbiter capabilities to transfer data from Mars surface assets to Earth. Mars landers, rovers, and aerial vehicles are mass- and volume-constrained, resulting in commensurate constraints on antenna size and transmission power. These constraints reduce direct-to-Earth (DTE) communications capabilities in comparison to orbiters. A communication-relay technique is used to address this problem: Mars surface spacecraft use higher data rates over short-range links to nearby Mars orbiters, which then transmit the data over the long distance to Earth. This relay results in increased data return, reduced energy requirements, reduced communications system mass, increased communications opportunities, robust critical event communications, and in-situ navigation.

Implementation of relay services requires ongoing operations support to coordinate these services across the participating NASA and international missions. It also requires the development of a number of agreements within NASA and with international partners, as well as participation in the International Mars Relay Coordination Working Group (IMRCWG). See also Section 3.2.1.

Program of Record: Research

> Advance research in the laboratory and the field to feed-from and feed-forward to missions at Mars.

MEP will continue to support Mars Research & Analysis (R&A) to maximize the scientific value of data returned. Programs such as the Mars Data Analysis Program (MDAP) support researchers in analyzing publicly available data from all Mars missions. MEP supports Participating Scientist Programs (PSPs) for a variety of missions, enabling researchers to influence mission operations and mission operations to influence research in a timely way. MEP coordinates with the broader Planetary Science R&A programs that also play key roles in supporting Mars-related research. These include Solar System Workings (SSW), Habitable Worlds (HW), Exobiology (EXO), Planetary Science and Technology from Analog Research (PSTAR), and more.

Program of Record: Sample Receiving Project

> Develop key technologies and facilities to ensure the SRP can prepare samples for study while implementing planetary protection and contamination control requirements.

The ongoing MSR campaign is a significant focus of NASA SMD resources. It would fulfill the long-term, highest priority goal of the planetary science community: to return to Earth scientifically selected samples from Mars for extensive analysis in terrestrial laboratories.

MEP has essential roles that bookend the MSR campaign: Mars rover *Perseverance*’s collection and caching of samples for Earth return and the SRP (Figure 21). SRP would be responsible for the development and operation of the Sample Receiving Facility (SRF). With community input, and following a heavily researched and validated protocol, MEP would design the SRF to provide initial sample characterization, sample safety assessment, and time-critical scientific analyses of the returned samples.

Ground facilities for the safe handling and study of samples returned from Mars are a necessary component for the MSR campaign. Similar facilities and instrumentation may be required by future human explorers and can benefit from lessons learned during the execution of SRP.

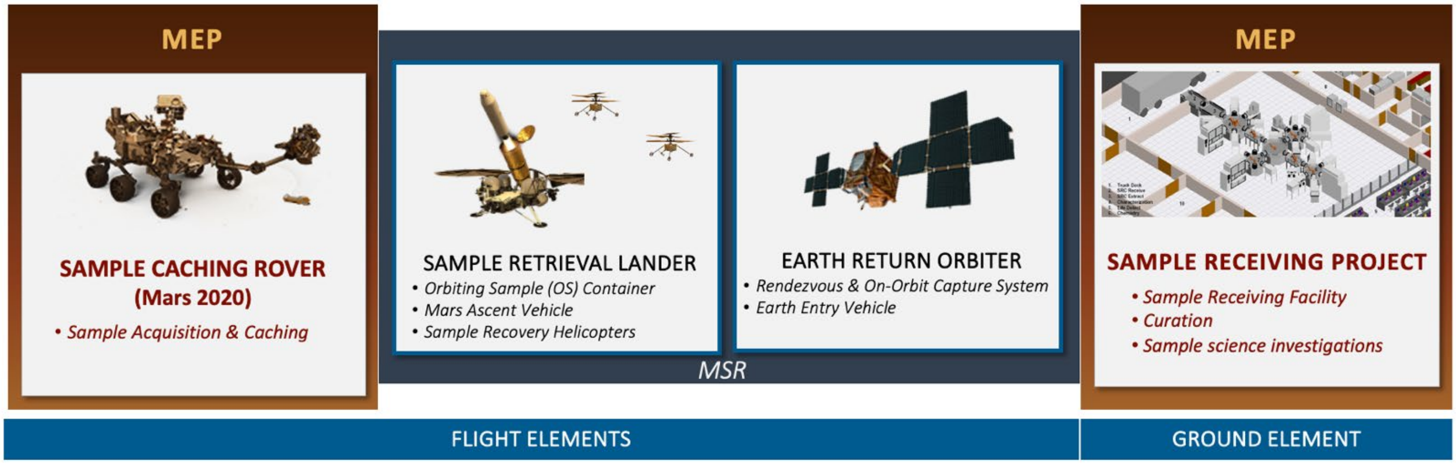


Figure 21. Relationship between MEP projects and MSR projects. At the time of this Plan’s publication, the MSR architecture was under review. *NASA/MEP*

With Mars rover Perseverance continuing to collect high-value samples and international experts designing a world-class Sample Receiving Facility, MEP is advancing its commitment to achieving the highest priorities of the planetary science community.

Samples returned from Mars must be handled in a high biosafety laboratory that offers an environment capable of preserving the scientific integrity of the samples, while strictly containing them until deemed safe or sterilized. Sample handling in a high biocontainment facility includes opening the sample tubes, extracting head gases, removing sample material, and packaging sample material for further analysis and distribution. MEP, in collaboration with ESA, began the development of such a facility under its technology program; future investments will continue through the SRP.

Establishing the priorities and methods for ensuring safety and for preserving sample information would also inform procedures to be used by humans on Mars when identifying samples for return or for directing new sample collection in the field.

Program of Record: International Partnerships

> Collaborate and coordinate with international partners to capitalize on shared interested and goals.

NASA has a long history of partnering in the exploration of Mars, with foreign science instruments contributed to MEP missions and NASA science instruments to international missions. These include:

- ***MRO:*** the Italian-provided SHAllow RADar (SHARAD) instrument;
- ***MSL:*** the Canadian-provided Alpha Proton X-Ray Spectrometer (APXS); the joint U.S.-French Chemistry and Camera (ChemCam) and Sample Analysis at Mars (SAM) instruments, and the joint Spanish-Finnish Rover Environmental Monitoring Station (REMS); and
- ***Mars2020:*** the joint U.S.-French SuperCam instrument suite, the U.S.-Danish Planetary Instrument for X-ray Lithochemistry (PIXL), the Spanish Mars Environmental Dynamics Analyzer (MEDA) instrument, and the Norwegian Radar Imager for Mars' Subsurface Experiment (RIMFAX) instrument.

NASA also supports co-investigators for two ESA ExoMars Trace Gas Orbiter (TGO) instruments: the Colour and Stereo Surface Imaging System (CaSSIS) and the Nadir and Occultation for MArs Discovery (NOMAD). Additionally, MEP supports collaborative science between synergistic mission teams (e.g., MAVEN, MRO, ESA TGO, and the United Arab Emirate [UAE] Hope orbiter).

MEP is also planning future international collaborations as part of its Program of Record. As the second component of its ExoMars program after TGO, ESA's upcoming Rosalind Franklin Mission (RFM) is designed to search for signs of past and present life on Mars and to characterize the water/geochemical environment. The Pasteur Payload, a suite of analytical instruments dedicated to exobiology and geochemistry research, would include the Mars Organic Molecule Analyzer (MOMA). NASA is designing the Mass Spectrometer subsystem (MOMA-MS), including electronics. NASA is also intending to support RFM by providing the launch vehicle, radioisotope heater units, descent engines for the RFM lander, and mission design and navigation.

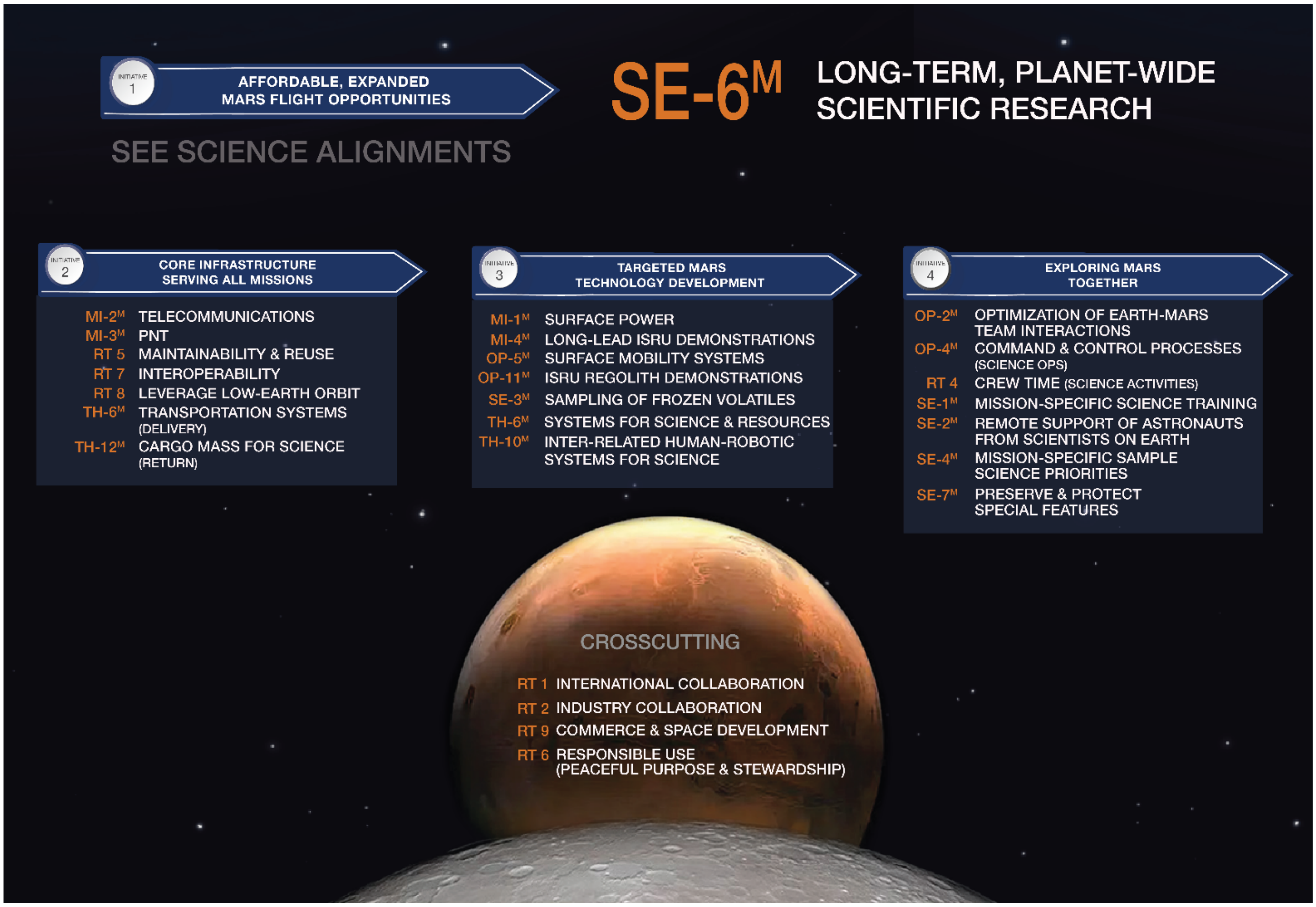
In the future, per OWL (2022) and other reports (see Appendix C), MEP will continue to explore international partnerships, including new effective models for them, as part of its lower-cost mission paradigm (see 3.1) and in support of NASA and international Moon to Mars objectives (M2M, 2023). MEP seeks continued relationships with established space agencies already conducting or soon planning Mars missions, while fostering new connections with emerging spacefaring nations.

Dusty water ice in Mars' Terra Sirenum. *NASA/JPL-Caltech/University of Arizona*

> *"Mars is a linchpin in the search for life and understanding Earth-like worlds, and small and medium missions targeting focused science questions will both make discoveries and drive new and better questions."*
>
> Dr. Bethany Ehlmann
>
> Principal Investigator,
> Lunar Trailblazer
>
> Director, Keck Institute for Space Studies, California Institute of Technology

> *"Recent technology advancements, coupled with emergent capabilities from the New Space sector, make it possible to explore new science objectives at Mars through bold and innovative approaches. Now is the time!"*
>
> Dr. Charles Norton
>
> Deputy Chief Technologist,
> Jet Propulsion Laboratory

These 2024–2044 initiatives (Sections 3.1–3.4) are intended to be considered and integrated throughout all MEP activities, thus ensuring forward progress in building the initiatives into the Program of Record. The initiatives are connected to and aligned with the NASA M2M Objectives (Figure 22).



INITIATIVE 1 AFFORDABLE, EXPANDED MARS FLIGHT OPPORTUNITIES

SEE SCIENCE ALIGNMENTS

SE-6^{M} LONG-TERM, PLANET-WIDE SCIENTIFIC RESEARCH

INITIATIVE 2 CORE INFRASTRUCTURE SERVING ALL MISSIONS

MI-2^{M} TELECOMMUNICATIONS
MI-3^{M} PNT
RT 5 MAINTAINABILITY & REUSE
RT 7 INTEROPERABILITY
RT 8 LEVERAGE LOW-EARTH ORBIT
TH-6^{M} TRANSPORTATION SYSTEMS (DELIVERY)
TH-12^{M} CARGO MASS FOR SCIENCE (RETURN)

INITIATIVE 3 TARGETED MARS TECHNOLOGY DEVELOPMENT

MI-1^{M} SURFACE POWER
MI-4^{M} LONG-LEAD ISRU DEMONSTRATIONS
OP-5^{M} SURFACE MOBILITY SYSTEMS
OP-11^{M} ISRU REGOLITH DEMONSTRATIONS
SE-3^{M} SAMPLING OF FROZEN VOLATILES
TH-6^{M} SYSTEMS FOR SCIENCE & RESOURCES
TH-10^{M} INTER-RELATED HUMAN-ROBOTIC SYSTEMS FOR SCIENCE

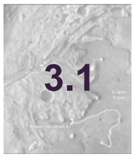
INITIATIVE 4 EXPLORING MARS TOGETHER

OP-2^{M} OPTIMIZATION OF EARTH-MARS TEAM INTERACTIONS
OP-4^{M} COMMAND & CONTROL PROCESSES (SCIENCE OPS)
RT 4 CREW TIME (SCIENCE ACTIVITIES)
SE-1^{M} MISSION-SPECIFIC SCIENCE TRAINING
SE-2^{M} REMOTE SUPPORT OF ASTRONAUTS FROM SCIENTISTS ON EARTH
SE-4^{M} MISSION-SPECIFIC SAMPLE SCIENCE PRIORITIES
SE-7^{M} PRESERVE & PROTECT SPECIAL FEATURES

CROSSCUTTING

RT 1 INTERNATIONAL COLLABORATION
RT 2 INDUSTRY COLLABORATION
RT 9 COMMERCE & SPACE DEVELOPMENT
RT 6 RESPONSIBLE USE (PEACEFUL PURPOSE & STEWARDSHIP)

Figure 22. Alignments between MEP Initiatives and M2M Objectives. The four new initiatives will be infused throughout MEP activities and are well-aligned with existing M2M Objectives. *NASA/MEP*



3.1 INITIATIVE 1: AFFORDABLE, EXPANDED FLIGHT OPPORTUNITIES

Explore Mars through Competed, Lower-Cost, and More Frequent Flight Opportunities

> Establish a regular cadence of science-driven, lower-cost mission opportunities as a new element of the MEP portfolio to address the breadth of outstanding Mars questions and to enable increased participation by the diverse Mars science community.

To maximize scientific progress in a cost-effective manner, MEP's first initiative sets out to transform the way in which Mars exploration is conducted. The aim is an affordable, regular cadence of missions that takes advantage of as many Mars launch opportunities as possible, allowing rapid response to discoveries and innovations. In support of this MEP 2024–2044 Plan, this achievement would also open up more space exploration opportunities for a diverse cross-section of both emerging and experienced partners and participants.

In this pursuit, programmatic balance is key, with an appropriate mixture of small- and medium-class missions, as well as the ability to take advantage of high-value missions of opportunity when possible. In all cases, the selected mission class would appropriately align with the science to be achieved (MASWG, 2020). Regardless of mission size and type, MEP must steer away from its traditional approach of highly customized, extremely low-risk space systems that must meet, each on its own, complex launch, delivery, telecommunications, and other operational needs. This approach produces highly successful, yet higher cost, missions, along with development schedules that result in disadvantageous swings in MEP's budget profile.

Success depends on a paradigm shift that nurtures a greater reliance on partnerships. Readiness for this approach fortuitously comes at a time when industry capabilities have evolved to a point when it is increasingly possible to leverage demonstrated commercial expertise and robust economies of scale, built up through studies of the Earth environment and recent investments in commercial services for ISS and lunar exploration. Getting to, and operating in, the Martian system does pose some unique challenges compared to those encountered by Earth-orbiting, cislunar, and lunar missions. However, MEP can leverage the immensity of prior research, development, and demonstration in those systems, investing in relatively minimal modifications for the Martian context. Additionally, international interest and capability in Mars exploration is growing, with many other countries having or actively planning a presence at Mars. With a higher cadence of missions regularly going to Mars, whether U.S. based or supported elsewhere, MEP can act as an early anchor investor to meet its scientific goals, while supporting U.S. commercial competitiveness in deep space.

3.1.1 *Lower-Cost Missions*

> *Enable broad, competed scientific investigations that address the full host of community-defined questions and encourage the incremental development of networks.*

MEP recognizes the transformative potential of emphasizing a strategic shift toward lower-cost spacecraft, with reducing unit costs as a key goal. This approach aligns with the input from the Mars science community (MASWG, 2020; LCSMC, 2022; MCE-SAG, 2023), suggesting that missions in the \$100M–\$300M range (estimated in real year dollars, excluding launch services) could return compelling and diverse results along multiple lines of inquiry for both fundamental Mars science and science for human exploration. Past lower-cost Mars missions showcase the capability of CubeSats and Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adapter (SPA) modules (known as ESPA). ESPA-class delivery systems can achieve key scientific and technological objectives, as exemplified by MEP's Mars Cube One (MarCO) CubeSats, the Mars helicopter *Ingenuity*, and the Small Innovative Missions for Planetary Exploration (SIMPLEx) program's Escape and Plasma Acceleration and Dynamics Explorers (ESCAPADE) mission scheduled to launch in 2025.

Particularly in support of Science Theme 3, studying Mars as a dynamic planetary system requires a transformation in the way in which Mars exploration takes place. It relies on continuous global data, with constellations of instrumented spacecraft making complementary measurements, with the right mixture of in-orbit and surface assets to meet the objectives. To make the kind of global studies already possible at Earth affordable at Mars, MEP must shift part of its portfolio from largely specialized, highly reliable, large-scale spacecraft to lower-cost spacecraft that are interoperable, upgradable, replenishable, and scalable over time. With a more frequent cadence of missions, MEP can create a positive feedback cycle that enables further cost reductions through standardization, reuse of designs, higher risk tolerance, heritage of off-the-shelf components, streamlined system engineering processes, and the ability to demonstrate and deploy more frequent incremental technology improvements.

MEP envisions implementing a high cadence of lower-cost, focused missions that feature either a single instrument or a small complement of instruments. These missions would be competitively selected with flexible timelines, providing the Mars science community with more frequent opportunities to conduct investigations of merit. Not only does that support the health of the profession and more diverse inclusion, but this strategy also serves to keep U.S. scientific leadership—uniquely built over 50 years—at the forefront of Mars exploration. The planned solicitation model would involve one or more awards per Announcement of Opportunity (AO), possibly occurring each launch opportunity or every other launch opportunity, with the overarching aim of launching one or more missions approximately every 26 months. This approach provides MEP with the flexibility to select and to execute multiple missions per opportunity based on individual project costs. MEP would also draw on NASA public-private partnership models (e.g., COTS, CLPS) to guide its own development of similar commercial services for these lower-cost missions.

3.1.2 *Medium-Class Strategic Missions*

> *Enable targeted or discovery-responsive scientific missions that address strategic, highest priority decadal class themes.*

Medium-class strategic missions to address decadal survey science priorities are an integral component of MEP's plan. With a tentative plan to launch approximately once per decade, these missions are targeted for a budget in the range of \$1–\$2B (about the scale of missions in NASA's New Frontiers program). The science objectives for these missions draw from, and are consistent with, various sources (primarily OWL, 2023), as well as OWL-consistent reports such as MASWG (2020), MCE-SAG (2022), science aspects of NASA's Moon to Mars objectives (M2M, 2023), and other community reports (see Appendix C). While adhering to the guidance provided by these documents, MEP also acknowledges the need for flexibility to accommodate evolving discovery-driven or Agency-prioritized objectives.

Medium-class strategic missions are characterized by more complex instrument payloads, featuring competitively selected or partner-contributed instruments. The most recent decadal survey (OWL, 2023) suggests two potential missions that could fit into this category of missions: a landed life-detection mission at a mid-latitude, ice-accessible location; and an ice-mapping mission, which could serve as a potential precursor to such a life-detection mission, as well as inform human-mission planning. MEP remains attuned to emergent priorities within this mission class, recognizing the need to adapt to evolving scientific and human exploration objectives, including potential advancements in human exploration outlined in OWL (2023). For medium-class strategic missions, MEP seeks international and public-private partnerships and other opportunities to lower their costs and increase their scientific return.

3.1.3 *Missions of Opportunity*

> *Open greater access to Mars for more participants by expanding lower-cost flight opportunities.*

With the intent of lower-cost Mars missions and more frequent science opportunities, MEP will actively seek high-value opportunities to participate in international missions of partner agencies. Participation in such missions of opportunity can include contributions such as hardware, science payloads, and ridesharing opportunities with cost-shared launch services. Missions of opportunity can be science focused or can address infrastructure needs.

To do so, MEP must develop programmatic flexibility, agility, and readiness to respond to both prospective and unanticipated opportunities. Similarly, MEP also envisions a future when U.S. Mars-bound missions of opportunity become platforms for international, commercial, and university participation, either through the integration of hosted payloads (spacecraft or scientific instruments) or through ridesharing opportunities on delivery systems that may increasingly be provided by the commercial sector in the future (see infrastructure).

Missions of opportunity can provide a strategic bridge among diverse entities, enabling both cost- and risk-sharing. With options for both competed and directed payloads, this approach holds the potential to democratize access to Mars exploration. By welcoming a broader array of participants, including new entrants, the exploration community can capitalize on a richer pool of talent, ideas, and resources. MEP seeks opportunities to fly payloads hosted on Mars-bound commercial service or international missions, as well as provide similar opportunities to others on NASA missions when there is excess capacity. Partnerships and new models for them (Section 3.4.1) are essential to the success of these mission opportunities.

Opportunities to work in partnership with the U.S. commercial space sector will be critical not only to mission success but also to the growing capacity for abundant science at all levels of investigation, from targeted questions to complex, high-priority inquiries, including those related to global systems science. These opportunities contribute to maintaining and expanding U.S. leadership in deep-space exploration, both in science and in industry.

3.1.4 *New Models for Expanded Mars Missions*

MEP is actively developing new business models for government-industry partnership (see also 3.4.1). Commercial capabilities in the space sector have grown significantly, along with partnership models designed to capitalize on industry's economies of scale and competitive practices. While these capacities are currently emerging for near-Earth and lunar applications, MEP is intent on examining how they might ultimately be leveraged for Mars exploration as well (Figure 23).

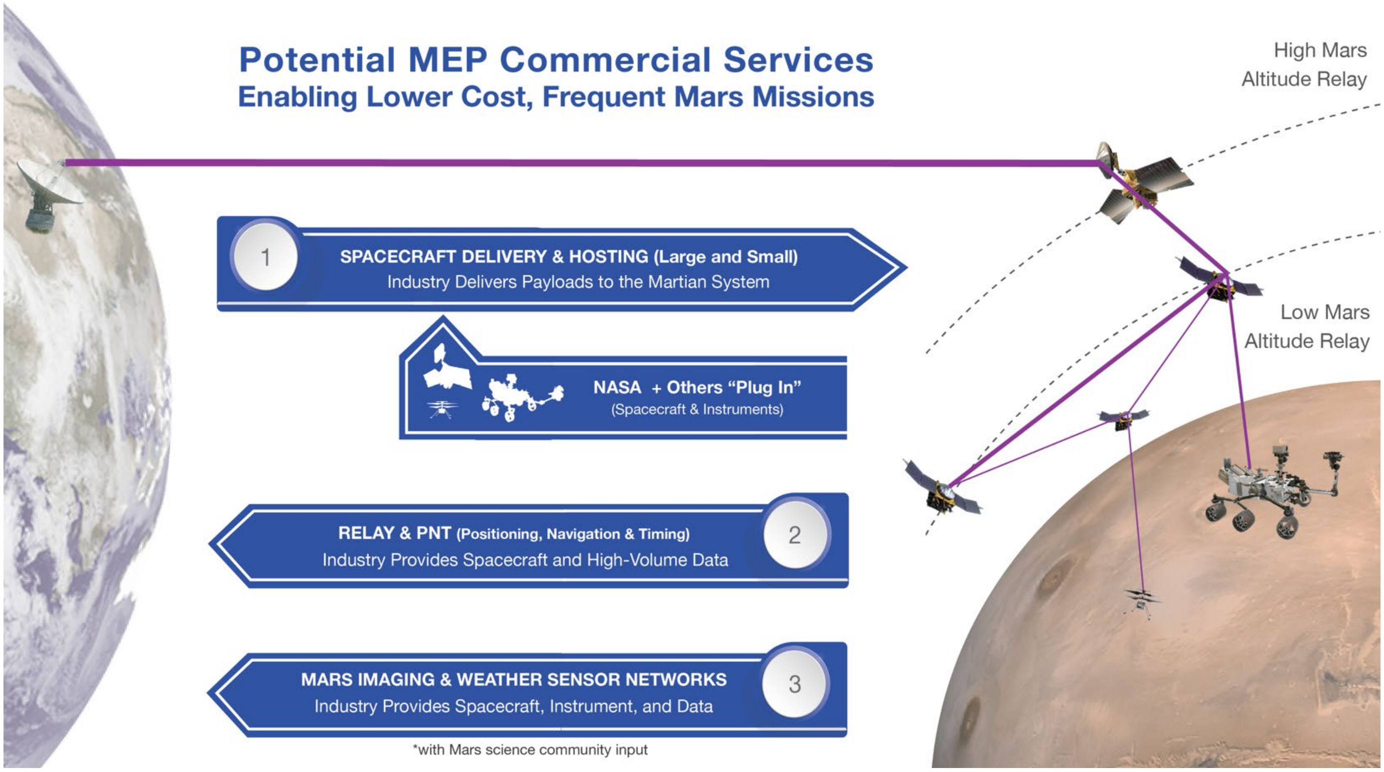


Figure 23. Potential for systems science. U.S. industry could provide three high-priority MEP commercial services for lower-cost Mars missions: delivery/hosting, communications relay, and imaging and weather sensors that provide long-term continuity and context for multiple missions and aid in mission planning. *NASA/MEP.*

Industry capabilities have grown significantly in the past few decades with some space-sector leaders capable of planning their own Mars missions. MEP supports the development of U.S. economic competitiveness in space, while leveraging industry capabilities for lower-cost, more abundant mission opportunities. MEP can help kickstart a proto-market for Mars services by acting as an anchor investor by providing an initial, stable funding profile with regular and frequent missions.

Having lower-cost services for common functions will significantly reduce entry barriers. Not only will more frequent and affordable NASA scientific missions be possible, but the doors will also be open to more participants such as universities (including those serving under-represented populations), small- and medium-sized companies (including start-ups), members of nonprofit Mars-interested organizations, and emerging spacefaring nations.

The U.S. commercial space sector gains from having a wider and more assured customer base beyond NASA as the anchor. NASA benefits from potential shared-cost contributions from other participants, along with lower and more competitive costs as industry gains experience in the Mars environment and deep space in general.

Building this capability maintains and advances U.S. scientific and technological leadership across academic, commercial, and governmental sectors. NASA has successfully demonstrated public-private partnership models in which government-industry partners share technologies, costs, and programmatic, technical, and schedule risks. For example, the COTS program has successfully used this model to develop new capabilities at reduced cost and in less time than through traditional contracting mechanisms. NASA’s CLPS initiative began competitively selecting eligible commercial vendors for end-to-end commercial payload delivery services to support future NASA lunar missions. Following the COTS/CLPS models, NASA is also transitioning from provider to customer for its SCaN program. By 2025, SCaN plans to rely primarily on commercial communications services for near-Earth missions, benefitting from cost savings through competitive pricing. This progress may have relevance to Mars, as capitalizing on economies of scale and public-private partnership models could significantly lower costs.

Illustration of Perseverance rover on Mars. *NASA/JPL-Caltech*

"The Mars rover Perseverance benefits enormously from the high data rates and high reliability provided by orbiters in the Mars Relay Network—MRO, TGO, and MAVEN. This relay network enables us to send back extremely rich scientific data, much of it imaging. Along with data relay, high-resolution imaging from orbit is critical to the efficient, routine operation of the rover and almost all of its science and mobility planning.

Without next-generation relay and high-resolution imaging, future missions would be extremely challenged in landing safely, identifying scientific regions of interest, navigating mobility challenges on the surface, and maximizing the volume of data returned."

Dr. Ken Farley
Mars 2020 Project Scientist
Professor of Geochemistry,
California Institute of Technology

3.2 INITIATIVE 2: CORE INFRASTRUCTURE SERVING ALL MISSIONS

Strengthening and Broadening Infrastructure at Mars to Enable a Diverse Set of Missions

> Enable infrastructural advancements that no single mission could likely achieve alone and that lower the costs and risks of, and increase benefits for, all Mars missions. Actively consider opportunities to buy commercial services to address MEP infrastructure goals.

Requirements/implementation approaches will be coordinated with other NASA Mission Directorates, as relevant.

A defining characteristic of MEP is the interconnected nature of its various program elements. As opposed to a sequence of standalone missions, MEP is structured as a loosely coupled program, enabling achievement of more than just the sum of its individual parts. In addition to the important scientific linkages among missions, with the discoveries of one mission posing new questions that drive the science goals of subsequent missions, MEP projects also emplace long-term capabilities that multiple missions can utilize.

MEP can make critical investments in augmenting current (and aging) capabilities that support multiple scientific inquiries. Replenishing and upgrading the Mars telecommunication network is essential to ensuring the continuation of existing communications with surface rovers, as well as expanding data return from user missions, while reducing their telecommunication requirements (mass, power). With multi-mission scientific relevance, replenishing and upgrading high-resolution imagery supports future missions in landing-site characterization and selection, including hazard assessment and surface-operations planning. Similarly, providing continuity in atmospheric data critical to Mars climatology investigations also enables the ability to quantify atmospheric conditions for arriving Mars surface missions (including monitoring and predicting hazardous dust storm events that can impact landed missions).

In addition to augmenting current infrastructure, MEP could invest in other cross-cutting capabilities such as establishing a commercial capability for lower-cost spacecraft delivery and payload-hosting services, and the development of multi-mission data-analysis tools to facilitate more efficient and complete studies of the wealth of returned Mars science data. By establishing cross-cutting capabilities that benefit all missions, these infrastructural investments represent key contributors to MEP’s goals for a lower-cost, high-cadence Mars mission paradigm. Highlighted here are key target infrastructural investment areas and the role they can play in the MEP 2024–2044 Plan.

3.2.1 *Mars Relay Network*

> *Build an interoperable, replenishable, scalable MRN for the high-rate return of large volumes of quality data from multiple landed and orbital assets, as well as PNT services.*

Today's MRN is perhaps the clearest example of MEP infrastructure. The program has ensured that, in addition to achieving their own primary science objectives, Mars orbiters carry ultra-high-frequency (UHF) proximity-link payloads. These payloads specifically allow the spacecraft to deliver enhancing and enabling relay services to other Mars missions. This strategy has enabled a large increase in the data returned from rovers and landers on the Martian surface. Mass- and energy-constrained, these surface assets can only support very limited DTE data rates. Relay links to current MRN orbiters support much higher data rates with greatly reduced energy-per-bit requirements, resulting in more than a tenfold amount of data return to the Deep Space Network (DSN).

The current MRN is a truly international endeavor, with multiple orbiters from NASA and ESA providing interoperable services based on their common implementation of international standards for space data. MRO, MAVEN, and ExoMars/TGO currently serve as today's workhorse data-relay missions. All of these orbiters fly MEP's Electra UHF Transceiver, enabling current Mars rovers to achieve high-quality data volumes of over 1 Gb/sol (i.e., per Martian day). These assets are augmented by ODY's lower bandwidth relay (which was well-matched and heavily used by the InSight mission and before that by the MER missions) and backed up by ESA's Mars Express in case of an emergency.

However, MEP has an urgent need to begin the next phase of MRN development (Figure 24). All existing relay assets are well beyond their original design lifetimes. Thus, replenishment is essential to sustain a robust capability, even at today's level of service. Second, MEP's goal of frequent, lower-cost missions calls for extending relay services—which are currently limited to users on the Martian surface—to include future orbiters. Frequent, lower-cost missions also demand the incorporation of higher frequency directional relay links, capable of achieving further 10–100x increases in data return for suitably equipped user missions.

Imagine an interplanetary internet for robotic and human exploration, built incrementally and affordably, leveraging significant prior NASA and commercial lunar investments with marginal changes for Mars and maximizing compatibility using international standards.

In partnership with NASA's SCaN program, MEP can pursue a time-phased approach, building toward a high-volume, high-data-rate communications infrastructure. A next-generation, replenishable, scalable, and interoperable MRN would provide reliable, near-continuous support to surface and in-orbit users, greatly increased instantaneous data rates for proximity links at Mars, and vastly higher Mars-to-Earth data rates, offering next-generation trunk-line capabilities. The evolving MRN architecture must accommodate the needs of a diverse set of user missions:

- low-altitude relay orbiters can continue to offer the most energy-efficient links for energy-constrained users that employ omnidirectional antennas (e.g., simple lower-cost landers, aerobots, etc.); and
- higher altitude orbiters with higher frequency, directional proximity links can offer increased relay availability and 10–100 Mb/s (or higher) relay data rates for suitably equipped orbiters and landers.

Combined with improved trunk-line performance for the relay orbiters, a next-generation MRN could support aggregate data return of more than 1 Tb/day from the Red Planet, enabling vastly increased science return from a diverse set of Mars missions. MEP can apply multiple strategies to achieve these goals. Development of reliable, lower-cost Ka-band DTE links for future MRN orbiters would support large increases in trunk-line capability. Selection of new

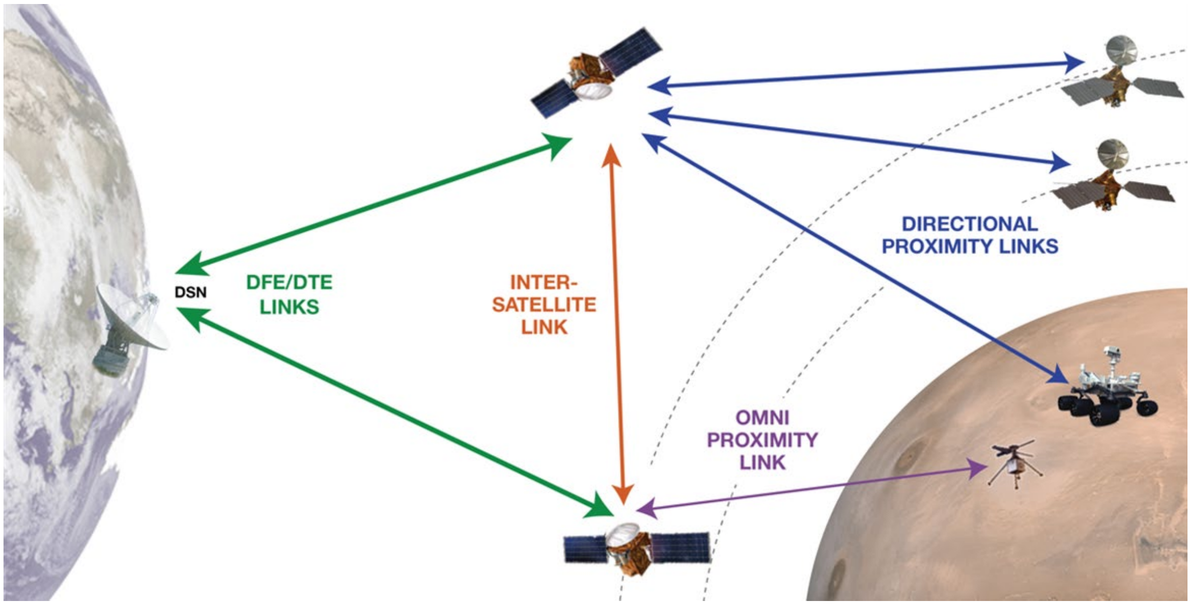


Figure 24. Notional depiction of future MRN scenario. *NASA*

higher frequency bands for directional proximity links (with options for S, X, K, and optical) would enable enormous increases in relay user data rates. Dedicated commercial satellites could provide future MRN services through hosted relay payloads on future science orbiters and/or on spacecraft delivery vehicles after they complete delivery of their payloads to Mars orbit.

While emphasis to date has rested on MRN telemetry services, the development of PNT services would support new use cases (e.g., orbit determination for small orbiters without DTE capability) and prepare NASA for human exploration navigation capabilities. Targeted investments in key telecom components, including transceivers, antennas, and power amplifiers, would ensure robust flight implementation solutions, both for future relay orbiters and a wide range of relay users.

In partnership with other NASA Directorates, MEP can play a significant early role in developing, expanding, and testing integrated Moon/Mars approaches and acquisition strategies for deep-space relay services. The MRN would seek to leverage capabilities and standards implemented in building up a similar infrastructure at the Moon (Figure 25). Considerable potential benefits include cost savings, reduced risk, interoperability, scalability, supply-chain diversity, and replenishment potential. MEP can take advantage of industry’s experience in space telecommunications services, leveraging economies of scale and manufacturing environments that rely on identical and repeatable spacecraft assemblies. International participation is also possible, building on today’s interagency MRN, via coordination through organizations such as the International Mars Exploration Working Group (IMEWG), the IMRCWG, and the Interagency Operations Advisory Group (IOAG).

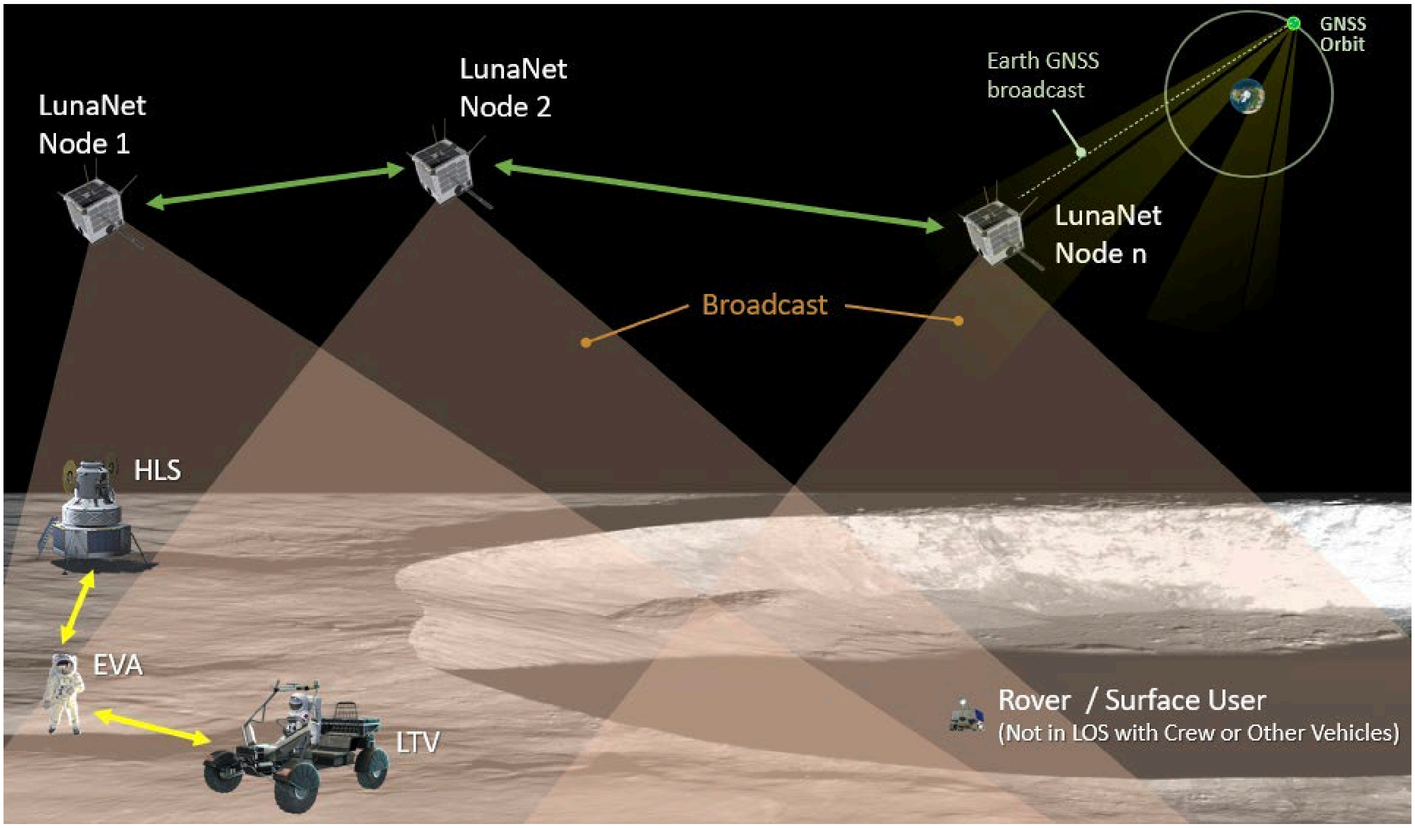


Figure 25. Artist's concept of LunaNet. *NASA/SCaN*

3.2.2 *Spacecraft Delivery and Payload-Hosting Services*

> *Leverage emerging capabilities to establish lower-cost methods for delivery of multiple spacecraft and/or payloads to Mars orbit or to the Martian surface.*

The high cost of delivering multiple spacecraft and payloads to Mars is one of the key factors that distinguishes Mars (and other planetary) missions from Earth-orbit and cislunar missions. Emerging commercial capabilities offer pathways to reduce these costs significantly. A new paradigm for Mars exploration is possible through the development of spacecraft delivery concepts with propulsive stages capable of delivering multiple spacecraft to Mars orbit and/or Mars entry trajectories, as well as potentially hosting multiple payloads for extended operations at Mars (Figure 26).

> *Deliver multiple spacecraft to Mars using lower-cost delivery and payload hosting to explore the Red Planet the way we explore Earth —and soon the Moon.*

Coupled with a next-generation MRN (Section 3.2.1), such delivery services could enable simple, lower-cost spacecraft and payloads that no longer need to address the unique propulsion and telecommunications challenges of an interplanetary mission. For example, an Earth-orbiting-class CubeSat could be deployed by a spacecraft delivery vehicle into its science orbit at Mars. The vehicle could then return high-value, high-quality data volumes through a next-generation MRN supporting high-rate links to orbiters. Such a capability would revolutionize the per-mission cost of Mars missions and open the planet to a much wider range of explorers, including universities and emerging spacefaring nations. In addition, after fulfilling

Figure 26. MEP can leverage U.S. industry's growing capabilities for Earth and the Moon. *NASA*

their customer spacecraft delivery services, spacecraft delivery vehicles could serve as prime platforms for operating as a service for other Mars infrastructure (e.g., telecom relay, imaging, weather monitoring).

3.2.3 *High-Resolution Imaging*

> *Augment the capacity for continuous contextual imagery that enables landing site selection and characterization for both robotic and human-robotic missions; provides mission-enabling context for targeted, lower-cost flight opportunities; ensures data continuity from the past 25 years of observations; and contributes to monitoring changes more frequently and at higher resolution.*

High-resolution surface imagery has proven to be absolutely vital to the success of robotic landings and science planning (Figure 27). MRO's HiRISE camera offers the highest resolution images available to date, with a ground sampling distance of ~30 cm/pixel. Images at this resolution have helped identify candidate sites of highest scientific interest, while also detecting hazards (e.g., rocks, slopes, gullies) at a scale relevant to landed spacecraft, which is essential for characterizing engineering risks such as entry, descent, and landing (EDL) and surface mobility.

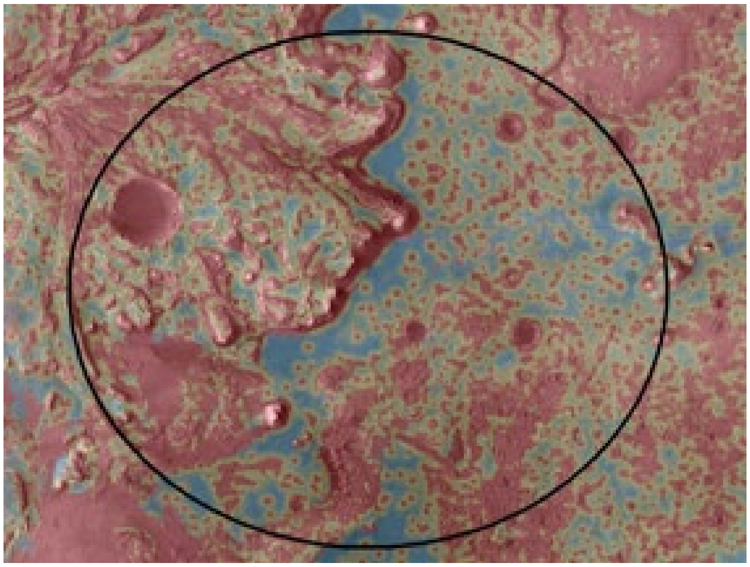


Figure 27. Hazard map for the Mars 2020 *Perseverance* rover. This false-color terrain map utilizes high-resolution imaging and digital terrain models to show safe and hazardous areas. *NASA/JPL-Caltech/U of A*

To reach the most compelling places, future robotic and human explorers must rely on improved capacity to distinguish safe landing areas (green and blue) from hazardous (red).

To date, only ~4% of Mars has been imaged at this 30 cm/pixel resolution. Operating far longer than its anticipated lifetime, MRO's HiRISE camera is exhibiting degradation and is not expected to be operational beyond the 2030s. Without replenishment and, ultimately, greater numbers of operating cameras, the continuity of high-resolution Mars observations is at risk—so too is the context for multiple missions and scientific investigations and the assessment of landing sites for future missions.

With the development of lower-cost, high-resolution imaging systems (and constellations of them) for Earth and lunar observations, MEP has the potential to augment current capabilities, perhaps even at resolutions that leapfrog current capabilities. Through public-private partnerships, MEP could lower costs in meeting this imaging need, while supporting U.S. commercial leadership beyond Earth and the Moon. Such an imaging capability would be developed with significant Mars scientific community input, enabling industry to provide the greatest science return.

3.2.4 *Weather Monitoring and Prediction*

> *Augment the capacity for continuous meteorological monitoring that ensures data continuity from the past 25 years, expands from monitoring to predicting weather, and progressively increases opportunities for coordinated orbital, aerial, and landed missions.*

Continuous and accurate weather monitoring is necessary to provide vital continuity and improvement of Martian weather records that extend back to 1997, building on the existing wide-angle, ultraviolet–visible–near infrared (UV-Vis-NIR) and infrared (IR) sounding/imaging data from Mars Global Surveyor (MGS), ODY, and MRO. Such weather monitoring provides timely measurements of atmospheric conditions prior to critical events, enabling improved mission planning for safe robotic and human-class landings, increasingly complex surface operations, and eventual launches from the Martian surface. In addition to weather monitoring, the expanded ability to predict local conditions would translate directly into future cost savings and risk reduction through mission planning, hardware optimization, and extreme-event mitigation (i.e., dust storms).

Current Mars orbiters in a traditional sun-synchronous orbit provide observations of meteorological conditions at only a few specific local times. This coverage is insufficient for accurate forecasting models. Incrementally building toward a modern meteorological network of orbital, aerial, and landed assets would support critical engineering needs and enable more comprehensive studies of Mars as a system. The addition of areostationary orbiters would provide continuous temporal, global, atmospheric, and meteorologic measurements. Spread at locations across the Martian surface, improved weather instrumentation would augment orbital coverage, contributing to the ability to predict the frequency and severity of local and global dust events. Such instrumentation could gather data at a higher frequency, include wind measurements, and/or characterize dust particles.

MEP will thus study coordinated and integrated plans for high-fidelity meteorology payloads hosted on next-decade robotic missions to Mars. In terms of mission-enabling partnerships, U.S. industry has built up formidable capabilities in studying Earth's weather. Lower-cost commercial services may be possible, both in terms of focused, standardized, single-purpose and networked spacecraft or as meteorological payloads that could be cost-effectively added to Mars-bound spacecraft. With community input, MEP can provide well-defined standards and measurement requirements to aid industry in achieving potential economies of scale with replicable, replenishable, low-cost networks of instruments capable of making comparable measurements (e.g., temperature, atmospheric density, dust, water vapor, water ice, and wind profiles).

3.2.5 *Ground Receiving Networks*

> *Advocate for a robust DSN as well as international and commercial alternatives to support the full range of Mars mission needs, including enhancing multiple spacecraft per aperture (MSPA) capabilities to allow more efficient simultaneous coverage of multiple Mars spacecraft.*

Higher data return increases the value of each mission and the nation's return on its overall MEP investment. Hand in hand with an evolving MRN is the need for a robust ground communication infrastructure here on Earth. Funded by NASA's SCaN program, the DSN embodies three globally distributed large complexes of antennas that enable command uplinks, data downlinks, and precision navigation (Figure 28).

If return on investment in Mars exploration is measured in data delivered per mission, receiving orders of magnitude more data back home through receivers on Earth would significantly expand the scientific potential of each Mars mission.

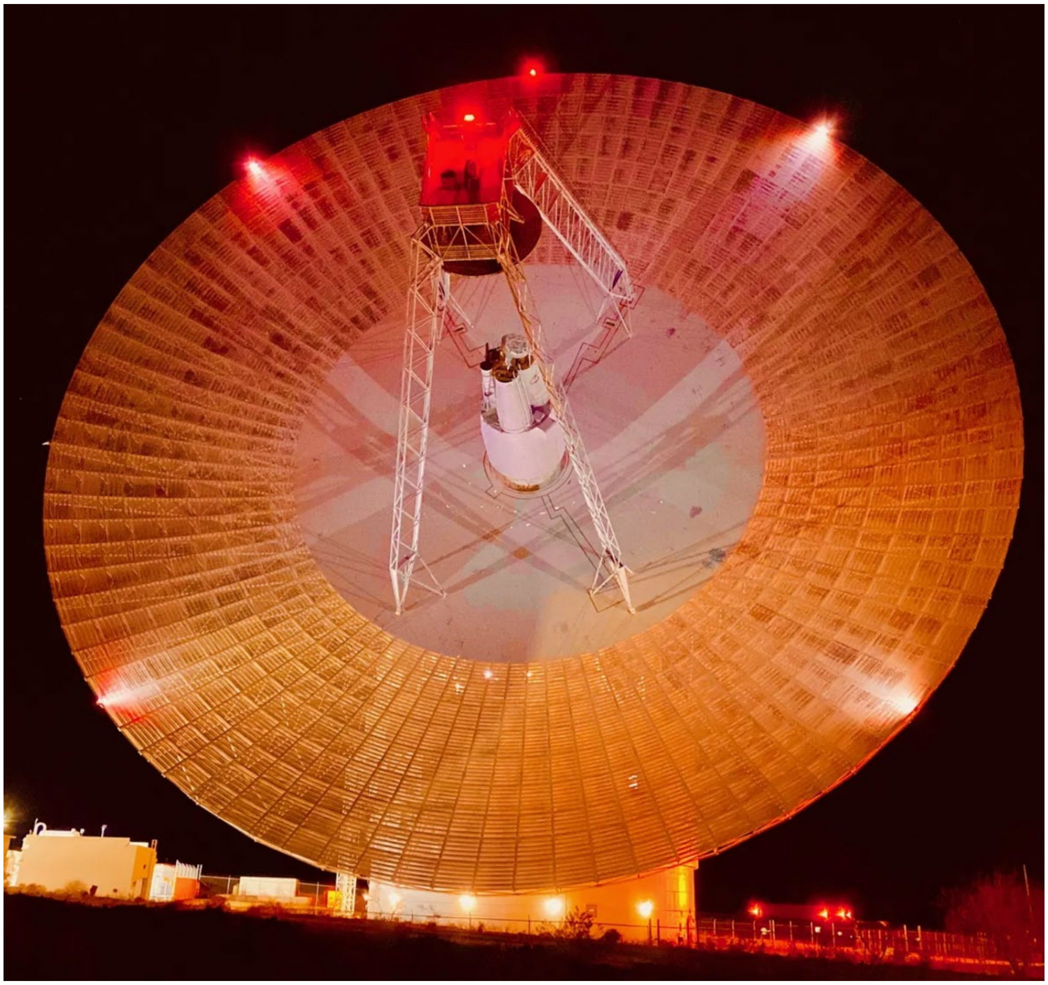


Figure 28. DSN support for Mars. DSN antennas have received voluminous data from Mars missions. *NASA/JPL-Caltech*

While MEP is not managerially or financially responsible for the DSN, it provides tracking services and confederated DSN scheduling services for all NASA (and ESA) Mars missions. Successful provision of these services requires ongoing care of the antennas, software infrastructures, the teams that operate them, and coordination on the use of the DSN by mission lunar space.

Of particular interest is the DSN's MSPA capability, which supports simultaneous downlinks from as many as four Mars spacecraft on a single DSN antenna. Given the number of lower-cost missions contemplated in the future, further development of the DSN's MSPA capabilities will be essential, including support for more simultaneous downlinks and adding a capability for multiple simultaneous uplinks.

Commercial and international provision of additional DSN-like antennas and services may become more essential as the number of missions and relay assets grows. MEP can also benefit from DSN investments in optical communications, which would efficiently enable significantly higher data rates and larger, high-value data volumes than those possible with Ka-band systems. MEP's long-term co-investment in developing MRN capabilities with SCaN and a potential Moon-Mars telecommunications infrastructure for both robotic and human exploration would support this capability.

Looking beyond planned improvements in radio-frequency-based DTE telecommunications, MEP will look to take advantage of NASA's longer-term development of an operational optical communications capability, building on the success of the current Psyche optical communications demonstration, to achieve even higher data rates between Mars and Earth.

Working together, as part of M2M Objectives, MEP and SCaN will seek opportunities to leverage lunar communications/navigation solutions and elements of the LunaNet architecture for application, where appropriate, at Mars, and to work with international partners to ensure efficient, interoperable communication and navigation services. See the 2022 IOAG report, *Volume 1. The Future Mars Communications Architecture*, for additional details.

3.2.6 *Data Infrastructure, Visualization, and Analysis*

> *Support strategic investments in data access, visualization, and analysis to expand research opportunities and to capitalize on existing and future mission data, the return of which will be orders of magnitude higher with the implementation of other infrastructure investments.*

The amount of data already returned from Mars is substantial, with much yet to be fully interrogated. Planned future relay capabilities could make available data staggering in both rate and volume and unprecedented in sophistication, quality, and continuity. Lower-cost, more frequent missions would increasingly provide the kind of monitoring possible in studying Earth's interacting systems: consistent and continual global coverage and coordinated measurements across networked orbital and surface platforms. No other destination in the solar system is yet prepared for that scale of observation. Long-term needs for human spaceflight also propel infrastructural capabilities, with opportunities to leverage nearer term lunar investments.

A healthy Mission Operations and Data Analysis (MO&DA) program is essential, yet it has historically been susceptible to underfunding and budget cuts. Responsive to science community and mission team input, MEP plans on continuing strategic investments in key systems. These include science planning tools such as the Multi-Mission Geographical Information System (MMGIS), Java Mission-planning and Analysis for Remote Sensing

(JMARS), and Mars Trek; data-archiving capabilities in the Planetary Data System (PDS); and Navigation and Ancillary Information Facility (NAIF) services (repository of trajectories and position data that are necessary to localize science results). Mission teams also develop and test innovations in augmented reality and visualization tools that make virtual and lifelike experiences of Mars possible for improved operations, data analysis, and experiences for the public.

With high-rate, high-volume, high-quality data from Mars through lower-cost missions and greater imaging capabilities, can we build toward a time of truly exploring Mars together when making a trip to Mars from living rooms is as easy as it is from a mission control room?

Figure 29. Advanced data visualization and analysis tools. Developing mapping and other tools that enable exploring the diversity of Martian terrain opens the planet to discoveries by scientists, astronauts (e.g., Buzz Aldrin at center), and the public alike, plus enables the characterization of candidate sites for both robotic and human exploration. *NASA/JPL-Caltech*

Artificial intelligence, machine learning, and other advances will be increasingly relevant to data mining, making big data from Mars and discovery with it more accessible. Through deliberative studies involving internal and external stakeholders and leveraging related NASA investments, MEP will seek high-payoff investments, including developing uniform standards, reconciling database discrepancies, tailoring artificial-intelligence and machine-learning technologies, and developing and testing augmented reality, virtual reality, and other interfaces that provide direct Mars exploration experiences (Figure 29).

Curiosity rover at the Mary Anning location on Mars.
NASA/JPL-Caltech/MSSS

"Technology development within the Mars Exploration Program has enabled revolutionary scientific discoveries for NASA and the world. Finding synergies for both the robotic and human exploration of Mars is critical for maximizing a return on investment. Together, we can advance game-changing technologies that enable us to achieve our shared Moon to Mars Objectives, accelerating the pace of exploration."

Michelle Munk
Chief Architect for NASA's Space Technology Mission Directorate

3.3 INITIATIVE 3: TARGETED MARS TECHNOLOGY DEVELOPMENT

Investments in Key Technologies to Enable Expanded Access to, and Scientific Understanding of, Mars

> Continue improving the capabilities of science-enabling missions that collectively enhance U.S. leadership in Mars exploration, lower the costs of all Mars missions, and build on the developments and experience gained from Earth-observing and lunar missions.

Requirements/implementation approaches will be coordinated across NASA Mission Directorates, as appropriate.

MEP technology investments over the past two decades have driven breakthroughs in capabilities needed to meet evolving, science-driven mission requirements. For example, technology investments in terrain-relative navigation, high-speed rover navigation, and sample caching have led to the success of the Mars 2020 *Perseverance* rover in exploring an ancient delta holding clues to Martian habitability and the potential for past life on Mars. The successful demonstration of the Mars helicopter *Ingenuity* was another high-payoff investment that validated the potential for future aerial vehicles to conduct scientific exploration and reconnaissance for robotic and human missions. More recent, MEP technology investments have advanced enabling capabilities for the MSR mission, including technologies for ascent from the Martian surface.

In the coming two decades, MEP investments in six critical technology domains would enable more affordable and capable missions, support the Mars science infrastructure, broaden accessibility for hard-to-reach areas of the surface of Mars, and improve access to the subsurface of Mars:

- Entry, descent, and landing;
- Surface and aerial mobility;
- Avionics, autonomy, and power;
- Drilling and sample handling;
- Mars science instruments; and
- Telecommunications.

These technologies are multipurpose and may benefit not only science missions but also human exploration efforts. In particular, MEP could leverage lunar technology development in the areas of avionics, autonomy, and power, as well as drilling and sample handling, and to a lesser degree, precision landing.

3.3.1 *Entry, Descent, and Landing*

> *Develop EDL technologies that lower the cost of access to the Martian surface and expand the boundaries of potential landing sites for a range of payload sizes and new landing site characteristics.*

EDL on Mars is uniquely difficult, due to the combination of its thin atmosphere and significant gravity. Enabling the vision of lower-cost, more frequent access to a larger fraction of the Martian surface, including higher elevations and rougher terrain, requires investment in the EDL domain. One potential approach to lower-cost access is to develop greatly simplified “rough” landers that could reach the surface safely without needing a parachute or propulsion system, with avionics and instruments that are ruggedized to survive large landing forces (Figure 30). Other potential approaches include lowering the ballistic coefficient of atmospheric entry systems by using deployable entry drag devices, reducing the cost and improving the performance of descent propulsion systems, and developing high-performance impact attenuation devices with lower mass and cost. Future aerial mobility systems could be deployed at altitude to avoid the need for a traditional landing system.

What if we could land safely almost anywhere**—at the most scientifically interesting sites at high elevations, with steep slopes, or rocky, hazardous terrain—**where we’ve never been able to go before?

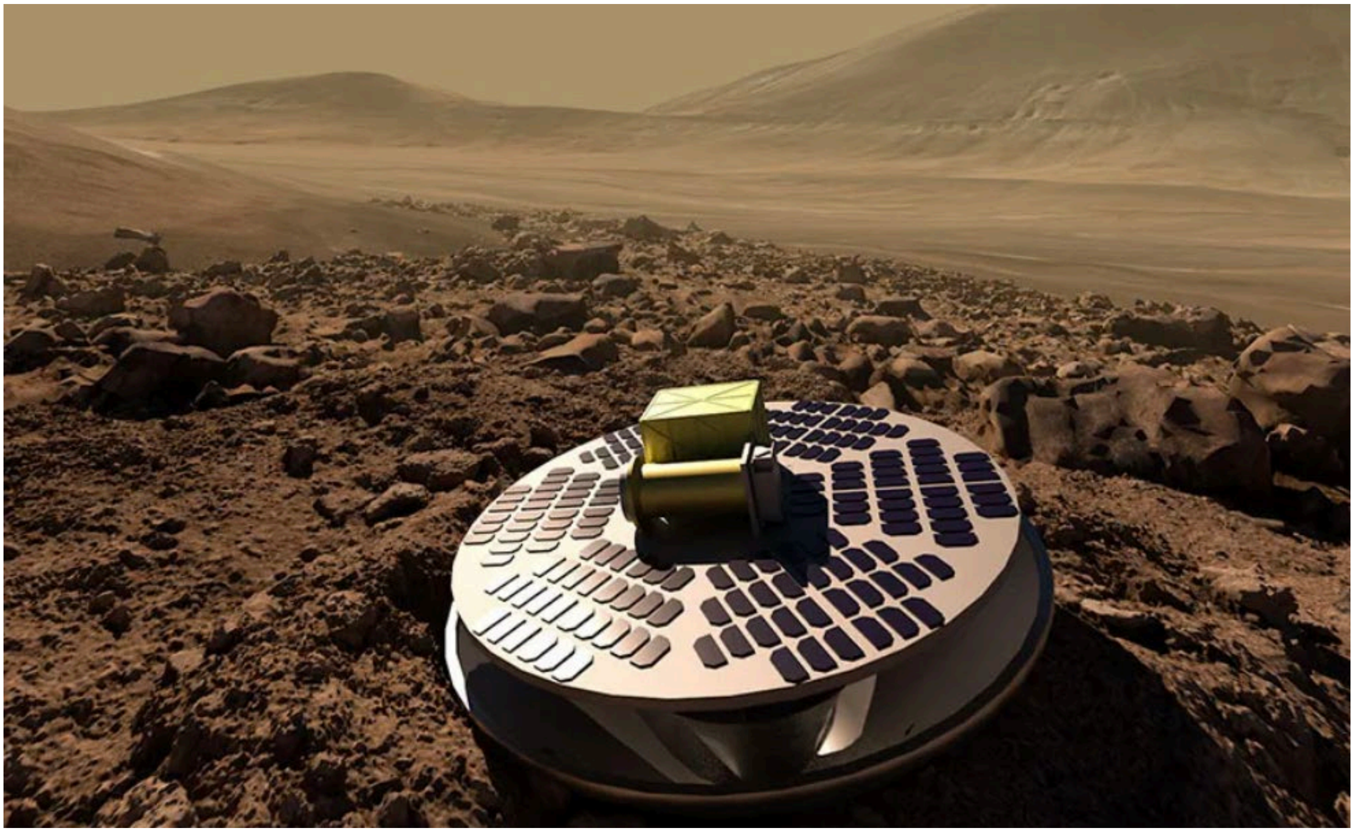


Figure 30. Rough lander concept. *NASA/JPL-Caltech*

3.3.2 *Surface and Aerial Mobility*

> *Develop technologies for much greater mobility on the surface and in the atmosphere to enable access to more challenging terrain and exploration over much longer distances than achieved by missions to date.*

Surface Mobility

Surface mobility with wheeled rovers has revolutionized Mars science in the past three decades. However, rover missions have become very expensive. Rovers are still strongly limited in their driving range per Martian day, in the difficulty of terrain they can traverse, and in the latitude range over which they can operate. New approaches are needed to reduce cost substantially, to increase range and agility, to broaden the classes of terrain that rovers (and crawlers and climbers) can negotiate, and to enable operation at higher, colder latitudes where less solar power is available.

Consider the potential to advance the next generation of agile, lower-cost mobile explorers to reach enticing hard-to-reach places waiting to be discovered.

The high power dissipation of avionics and the slow traverse rate of rovers to date strongly affect the energy budget, which limits driving range and latitude of operation. Low-power avionics and high-speed mobility actuators could revolutionize energy budgets and traverse rates. Heaterless actuators could reduce the mass, power, complexity, and cost of mobility systems, as well as of robot arms and pan/tilt masts needed for sensors, instruments, and sampling devices. This capability would enable greater range per day and operation at higher latitudes.

With investments in more capable avionics and autonomy, mobility mechanisms could become simpler and more agile than the six-wheel designs of prior rovers, which would lower cost and enable access to rougher terrain. Novel mobility mechanisms, including tethered vehicles,

Figure 31. New Mars mobility capabilities. Testing a versatile family of single-axle rovers designed to access high-risk terrain on planetary surfaces, such as steep slopes, and caves—areas that would be challenging or inaccessible for current Mars rovers. *NASA/JPL Caltech*

legged mobility systems, and climbing mobility systems hold the potential to broaden the classes of navigable terrain on Mars.

Dust-mitigation techniques for solar arrays would benefit both mobility systems and stationary landers.

Aerial Mobility

Figure 32. Mars helicopter *Ingenuity*. *NASA/JPL-Caltech*

The *Ingenuity* helicopter revolutionized Mars mobility by showing for the first time that rotorcraft flight is possible on Mars (Figure 32). *Ingenuity* used a coaxial, counter-rotating rotor system for its simplicity and high thrust-to-weight ratio. It used commercial-grade avionics components to provide high enough performance with low enough mass and power dissipation to enable controlled flight. *Ingenuity* showed that aerial vehicles can cover terrain that is impassable to rovers, with individual sortie ranges well beyond what rovers have done to date. Nevertheless, *Ingenuity*'s payload was limited to two cellphone cameras with a combined mass under 2 grams. Its traverse range was limited by its radio communication through the *Perseverance* rover. Its mission ended when it flew over terrain that was beyond the capability of its navigation system to maintain accurate velocity, altitude, and safe landing site knowledge.

> ***Imagine the potential for discovery*** *if a Mars helicopter could continually fly farther and farther away from its original location, transmitting its images and sensor findings directly to an orbiter.*

Investments are needed to enable aerial mobility with payload mass up to several kilograms, operation without needing other nearby surface assets for radio relay, and reliable navigation over any type of terrain. Achieving much greater payload mass requires much more thrust, which implies more blade area. These needs may lead to multi-copter designs or other classes of aerial mobility system with more lift. Such capabilities imply much more power for propulsion, which in turn needs advances in batteries with high specific power and energy storage. Operating without another surface radio relay requires a radio on the aerial mobility system that can communicate directly with orbiters. Improving navigation performance requires improved sensors, algorithms, and greater computing power. At the same time, the avionics must maintain very low size, weight, and power (SWaP); radiation fault tolerance; and the ability to survive cold overnight temperatures with as little heater power as possible.

3.3.3 *Avionics, Autonomy, and Power*

> *Develop inter-related advances through avionics miniaturization and ruggedization, much more onboard computing, more capable onboard autonomy, and higher power and energy storage. These capabilities would enable greater terrain access for mobility systems, fewer stops to call home for troubleshooting, higher mass fraction for instruments, and lower overall flight system cost.*

Avionics

Advances in avionics miniaturization and ruggedization are essential for enabling the next generation of lower-cost landers. More advanced onboard autonomy is central to enabling mobility systems to travel farther and to access more challenging terrain. This capability requires more onboard computing. NASA’s investment in High-Performance Space Computing (HPSC) will generate breakthroughs in low SWaP and high-performance onboard computing. However, such improved avionics systems may still be too heavy for aerial mobility systems and will not support the degree of machine learning–based autonomy that is available for robotics on Earth. Another route to these capabilities is to extend what was accomplished for *Ingenuity* by leveraging commercial-off-the-shelf processing elements developed for cellphone and smart-car markets. These commercial products now incorporate fault-tolerance features analogous to those traditionally used in space.

Advances in miniaturization and performance of sensors for guidance, navigation, and control (GNC) go hand in hand with advances in computing and autonomy. Huge progress has been made in this area for on-Earth applications of inertial sensors, cameras, and lidars. Leveraging this capability for applications on Mars could yield large benefits if cost and SWaP can be kept low. *Ingenuity* took steps in this direction by using cellphone cameras and inertial sensors; much more could be achieved in this area.

Autonomy

A central driver for autonomy is reducing the frequency of stops for mobility systems to call home for human help. Engineers currently use these ground-in-the-loop (GITL) cycles to update rover and aerial vehicle positions relative to orbital maps, to mark sand dunes as hazards because the robots cannot recognize them yet, to help plan paths through rocky terrain, and to diagnose and correct a wide variety of fault conditions that can occur. More onboard automation of these functions would greatly increase mission productivity by reducing time lost to GITL cycles.

Power

Aerial mobility systems in particular need batteries that can deliver very high current and store large amount of energy with low mass. Surface mobility systems would also benefit from batteries with much greater energy storage per unit mass. Rapid advances in battery technology for applications on Earth include electric cars and aircraft with analogous requirements. Leveraging this work for Mars applications could have great impact. *Ingenuity*’s battery survived a surprising number of cold Martian nights with no battery heating. Maintaining and extending such cold-temperature survival would be beneficial for both batteries and avionics components; enhanced thermal management technologies may also provide benefit in this area. Note that parallel advances in thermal technologies, including improved thermal management systems as well as new low-temperature actuators, can reduce thermal-related energy usage, minimizing system-level power requirements while freeing up energy for other in situ activities.

Power system cabling is relatively heavy, so new power-distribution techniques could save substantial mass. Dust accumulation on solar arrays is a long-standing issue that limits the lifetime of solar-powered Mars landers and mobility systems, and dust-mitigation techniques for solar arrays would benefit both landers and mobility systems. Past work toward small, radioisotope-based power sticks enables small lander science stations to run without solar arrays, including at high latitudes. It may be timely to revive such work to support affordable, long-lived lander networks for meteorology and regional seismology.

3.3.4 *Drilling and Sample Handling*

> *Invest in low-mass, high-performance, reliable drilling and sample-handling systems that extend subsurface access beyond the current depth limit of 2 m to depths of 10 m or more. Access to the subsurface would expand our understanding of Mars' geologic and climate history, investigate whether microbial life could have survived and evolved underground after the surface became inhospitable, and characterize the availability of water ice as a resource for future human missions.*

A primary scientific driver for accessing the subsurface of Mars is the search for evidence of past or present life. The surface of Mars is inhospitable due to radiation, oxidizing chemicals, extreme aridity, and cold temperatures. If life or prebiotic organic chemistry ever evolved on Mars, evidence might be found in the subsurface, at depths below the sterilizing effects of surface conditions. Present-day life may exist in thin films of water within shallow ice, in liquid inclusions in salt deposits, in caves, or in potential deep groundwater aquifers.

Subsurface access to greater depths in different locations is required to search for biosignatures in these refugia (Figure 33). Subsurface drilling would also enable probing aspects of Mars geologic and climate history that are not recorded on the surface or are masked on the surface by more recent alteration.

Another primary driver for accessing the Martian near-subsurface environment is to characterize the presence and extractability of water-ice resources in support of future human exploration at Mars.

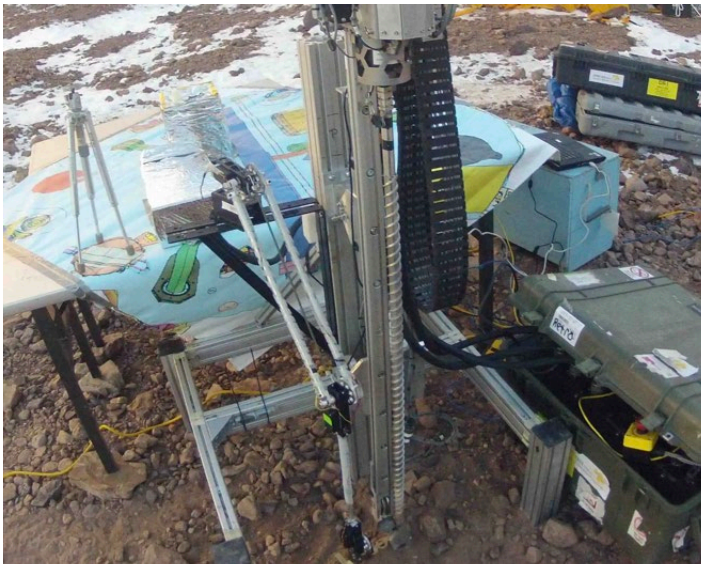


Figure 33. Mars-prototype icebreaker drill. This drill has been tested in Mars-like Dry Valleys, Antarctica. *NASA/ARC*

Being able to drill reliably into the unforgiving subsurface of Mars would advance the search for microbial life, improve our understanding of Mars' climate and geologic history, and assure astronauts of local water resources, reducing the costs and risks of living and working on the surface and during the journey back to Earth.

3.3.5 *Mars Science Instruments*

> *Ensure that instrumentation meets MEP needs for future potential lower-cost missions, for a medium-class strategic mission to search for evidence of extant life, and for robotic precursor missions ahead of surface human activities.*

Figure 34. NASA's BRAILLE (Biologic and Resource Analog Investigations in Low Light Environments) project explores Mars-like lava tubes on Earth. *NASA/ARC/JPL-Caltech*

The Decadal Survey (OWL, 2023) recommended an ambitious medium-class mission to explore for signs of extant life in or near areas with accessible near-surface water ice. This high-priority science objective would require advanced biosignature-detection instruments, as well as improved instruments to characterize environmental conditions and innovative mobility systems for hard-to-reach places (Figure 34). An instrument suite that could provide an unambiguous result is of paramount importance when tackling such a question. The combination of the right detection limits, the requisite context, and complementary data sets would be necessary to create forward motion in answering the questions about life at

Mars. Such a mission might require new techniques for planetary protection to avoid contaminating the Martian measurements with material brought from Earth.

> *Miniaturizing instruments, while advancing their measurement capabilities, can revolutionize scientific discovery by enabling more types of missions in scientifically compelling places.*

Enabling a new generation of lower-cost missions to address the breadth of Mars science discussed in Section 2 requires advances in other instrument technology to improve existing measurement capabilities and to enable new classes of measurements. Instrument miniaturization and ruggedization are also important for enabling lower-cost, more capable missions of all types (i.e., orbiters, landers, networks of landers, and mobility systems).

3.3.6 *Telecommunications*

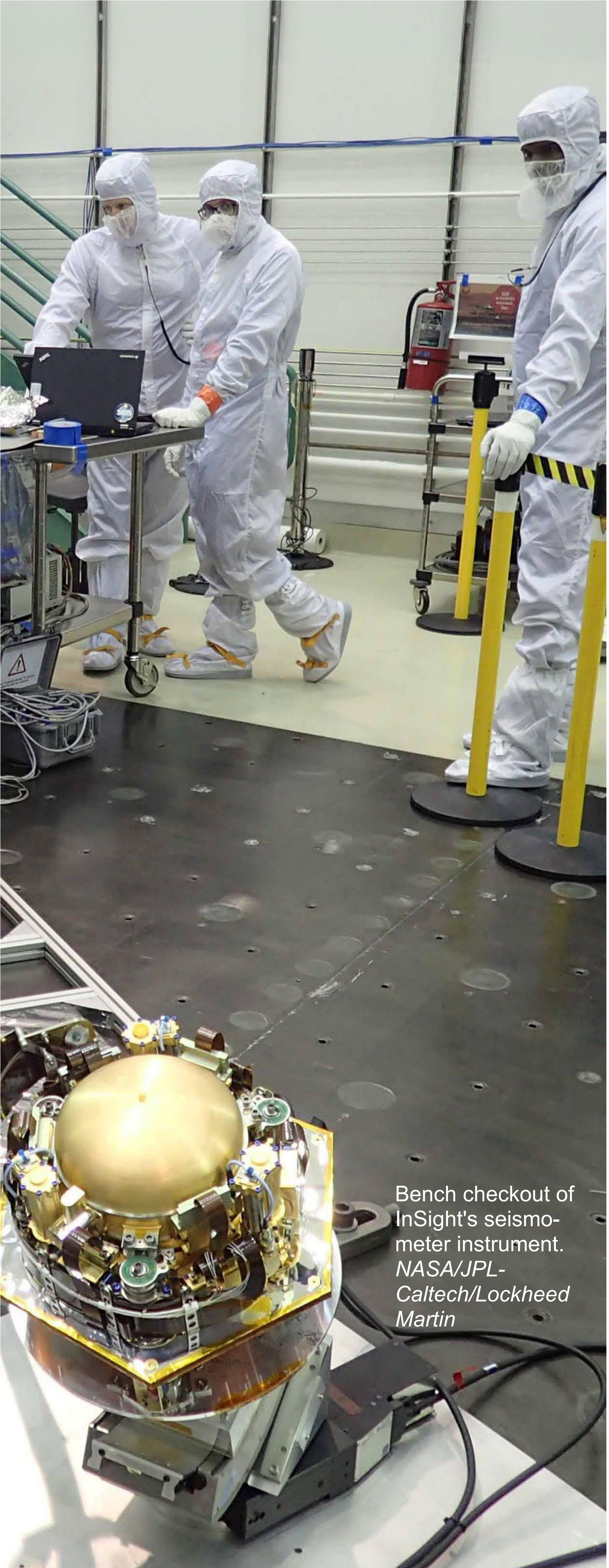
> *Invest in telecommunication technologies that go beyond replenishing the current MRN to enable standalone aerial mobility missions, greater relay capability from the surface to orbit, greater trunk-line (DTE) transmission to Earth, and intersatellite links that enable lower-cost science orbiters by eliminating their need to carry DTE capability.*

In addition to Mars telecommunication relay network replenishment needs and potential commercial services discussed elsewhere in this Plan, several telecommunications technology advances would greatly benefit future missions. As discussed in Section 3.3.2, standalone aerial mobility missions are not possible without developing a new, very low SWaP UHF radio for aerial vehicles that can communicate directly with orbiters. In addition, firmware and software updates for orbiters would enable further mass reduction for aerial vehicles (e.g., by using half-duplex signaling to eliminate the need for a UHF diplexer on the aerial vehicle). Small, lower-cost landers and lander networks have similar needs, and even surface mobility systems might benefit from being able to use such a radio.

To date, Mars orbiting missions have used very-low-gain antennas for UHF links with surface assets. Several potential approaches for implementing medium-gain UHF antennas on relay orbiters could substantially increase data throughput from the surface, with no change to surface assets. Extending relay services beyond UHF to higher radio frequencies and/or to optical wavelengths offers the potential for enormous increases in proximity-link data rates, but would require proximity-link transceiver solutions, including simple yet robust approaches to handling user pointing requirements of these narrower beam communication links.

The DTE link on orbiters to date has used rigid antennas. Deployable mesh antennas have been used in Earth orbit, but not yet on Mars orbiters. Maturation of these deployable antennas for Mars could reduce volume requirements in cruise and enable larger dishes for higher throughput. The future MRN envisioned by MEP and international partners would extend current services to enable relay among Mars orbiters. Future science orbiters would be able to relay their data to MRN orbiters carrying high-data-rate telecommunications subsystems and thus avoid having to carry their own DTE antennas, which would either reduce mass, volume, and power for the spacecraft; lower its cost; or provide extra mass/volume/power for additional onboard science instruments, thereby increasing return on investment. This next-generation MRN capability would also require new developments in intersatellite communication links suitable for the Martian environment.

Emerging protocols and standards will be key to achieving performance improvements and ensuring interoperability among spacecraft telecommunication links at Mars. Implementing the Unified Space Data Link Protocol and tailoring and deploying network-layer protocols (e.g., delay-tolerant networking) would achieve reliable and efficient end-to-end data transfer, particularly as the network topology at Mars grows more complex.



Bench checkout of InSight's seismometer instrument. *NASA/JPL-Caltech/Lockheed Martin*

“Partnerships with academia and the private sector are key to successfully exploring Mars, whether they are part of PI-led missions, strategic university research partnerships, or engaging smaller groups directly. Such partnerships result in cost savings and inspire the public in broader ways.”

Dr. Roger Wiens

Professor of Planetary Science, Purdue University

SuperCam Principal Investigator for NASA’s Perseverance rover

“Numerous studies and experiences have shown that welcoming and enabling participation of a wide range of folks is critical not only for fairness and equity, but also for expanding public interest in Mars exploration and significantly increasing the resources and ideas available for surmounting engineering challenges, answering key science questions, and defining inclusive and sustainable exploration practices.”

Dr. Serina Diniega

Mars Scientist, Jet Propulsion Laboratory, California Institute of Technology

3.4 INITIATIVE 4: EXPLORING MARS TOGETHER

Participation in Mars Exploration for All Communities

> Strengthen MEP activities that support NASA’s goals to develop partnerships; to train, sustain, and retain a qualified and diverse workforce; to develop scientific and technical literacy; and to foster a more inspired and informed society.

Requirements/implementation approaches will be coordinated with ESDMD, STMD, and SOMD, as appropriate.

The heart of this initiative is to foster diverse and inclusive participation in Mars exploration among individual, organizational, disciplinary, cross-sector, and international participants. Through its Policy Statement on Diversity, Equity, Inclusion, and Accessibility (DEIA) for NASA’s Workforce and Workplaces, NASA is entirely committed to the full participation and empowerment of a wide variety of people, organizations, capabilities, and assets to accomplish its mission. Diversity spans individual backgrounds and areas of expertise, small and large organizations, emerging and demonstrated experience in spaceflight, and a host of other talents and capabilities that can be brought together on behalf of discovery. Including diverse voices and participation fosters the development of a more impactful and relevant Mars Exploration Program.

3.4.1 *Mission-Enabling Partnerships*

> *Leverage partnership opportunities and new models of engagement to lower costs, capitalize on capabilities, and enable more diverse and inclusive participation.*

MEP proactively seeks to forge deeper partnerships with a variety of communities to build shared expertise, experiences, resources, capabilities, and rewards. These foundational, evolving, and new partnerships are essential to a future of affordable and achievable Mars robotic missions and, eventually, a sustainable human-robotic presence on Mars. Over the next two decades, MEP plans on proactively developing and strengthening partnerships with other NASA organizations, international partners, and industry. Crafting new and fulfilling means of opening and sustaining expanded opportunities among all Mars-interested individuals and communities, with a dedicated emphasis on those historically excluded, is a core MEP commitment.

Mars Science and Engineering Community

Since its initiation, MEP has recognized the critical importance of the science community in providing input to planning and prioritizing NASA's Mars scientific activities. MEP will continue to emphasize partnering with this community to develop the program's exploration strategy, driven by scientific discovery and hypotheses, and to seek the science community's input through the planetary decadal surveys, MEPAG, science steering groups, science-definition teams, and review boards.

U.S. Colleges, Universities, & Research Organizations

Partnerships with colleges and universities—the foundation of academia—and other research organizations continue the strong involvement of the science community and expand on it with opportunities to involve the next generation of scientists and engineers and to develop potential missions and payloads (Figure 35).

With spacecraft delivery and payload hosting a key focus of infrastructural development, opportunities for college and university to access Mars at a lower cost becomes more viable. In addition to developing, building, and operating science instruments, enabling students and faculty at colleges and universities to participate directly in Mars exploration could increase the breadth of scientific observations and prepare the next generation to be part of MEP activities.

MEP also recognizes the pivotal role of programs such as the Planetary Instrument Concepts for the Advancement of Solar System Observations (PICASSO) and the Maturation of Instruments for Solar System Exploration (MatISSE). MEP is committed to ensuring their sustainability. Such support paves the way for innovations and improvements to existing instruments, such as advanced spectrometers or novel drilling mechanisms that are essential for future Mars missions.

The ability to deliver small payloads at lower cost through MEP government-industry infrastructure development would open opportunities for university-led science and engineering programs to gain experience in spaceflight and Mars exploration.

U.S. Industry

Figure 35. Next-generation engagement in Mars missions. Interns Ashten Akemoto, Aden McKinney, Natalie Deo, and Patricia Meza in the Mars Yard, working on developing the future potential of small, multi-rover missions. *NASA/JPL-Caltech*

MEP is strategically positioning itself to leverage the growing capabilities of the commercial space sector for Mars exploration. Recognizing the advancements brought forth by industry, MEP seeks existing solutions that require minimal development adjustments to render them ready for Mars. This Plan steers away from bespoke spacecraft designed solely with Mars as a target to ones that can leverage existing hardware previously developed for the Earth and Moon. This transformative approach especially enables lower-cost space transportation and the establishment of a next-generation MRN (Section 3.2), thereby decoupling complex propulsion systems and DTE telecommunications.

International Community

Mars is becoming a compelling scientific destination for numerous international space programs, as demonstrated through growing numbers of planned missions and membership in the IMEWG and the International Space Exploration Coordination Group (ISECG), among others. Multiple nations have joined NASA in signing the Artemis Accords, a cooperative framework for the peaceful exploration of the Moon, Mars, and other solar system destinations; many regard their near-term plans for Mars as strongly tied to Moon to Mars ambitions.

NASA has a rich history in successfully partnering with other nations in a variety of modalities, including the contribution of instruments and subsystems to each other's missions, multi-mission capabilities and services (e.g., DSN coverage and communications relay for each other's missions), as well as multi-mission campaigns such as MSR. These and new partnership models are increasingly necessary to amplify science return, to minimize potential mission costs and risks, to encourage interoperability, and to take advantage of capabilities held by the partner nations.

NASA Mission Directorates

Coordination with other NASA Programs and Mission Directorates can identify shared needs and collaborative infusion opportunities (Figure 36).

Figure 36. A gathering of Moon to Mars architects. Experts from 18 countries, 85 aerospace companies, and 25 academic institutions gathered to share perspectives on NASA's Moon to Mars architecture. *NASA/Keegan Barber*

MEP commits to playing a key role in building mission-enabling partnerships within the Agency and beyond *to contribute to NASA and the nation's Moon to Mars ambitions.*

ARMD

Aeronautics Research Mission Directorate

As the Aeronautics Research Mission Directorate (ARMD) lays out a vision for 21st century aviation on Earth, MEP can seek to leverage transformative concepts that might be applied to a Martian context, in support of access to the most compelling places to explore on the Red Planet. While robotic spacecraft that might fly in the thin Martian atmosphere have unique challenges, ARMD's focus on advanced technologies and far-future concepts may provide unique, out-of-the-box insights that could expand possibilities for discovery in the Martian environment.

ESDMD

Exploration Systems Development Mission Directorate

ESDMD has overall responsibility for human missions to Mars. At the same time, a major objective for landing humans on the surface of Mars is to achieve decadal-level science. Increased coordination between MEP and ESDMD is key to achieving a shared vision of a sustainable human-robotic future on Mars when a human presence and human-class infrastructure can advance discovery far beyond current capabilities. In robotic missions prior to human arrival, MEP is committed to advancing M2M Objectives (particularly those related to science), seeking opportunities for synergistic science where connections between fundamental Mars science and science for human-mission planning can maximize the nation’s return on investment. MEP will also work closely with ESDMD to define and obtain data needed from Mars to ensure safe and cost-effective missions.

SMD

Science Mission Directorate

Part of SMD / Planetary Science Division (PSD), MEP science has many relationships to other disciplines within the Directorate. Science Theme 3 articulates strong connections between the Earth and Planetary Science Divisions. Many Mars upper atmospheric science investigations are closely tied to the Heliophysics Division and implications for space weather at Mars. MEP and the Astrophysics Division share the study of the origin and evolution of planetary systems and the quest to understand the potential for life in the universe. MEP can contribute to studies in the Biological and Physical Sciences Division through characterizations of the Martian environment that future human explorers would encounter.

SOMD

Space Operations Mission Directorate

SOMD is a key partner for MEP. The DSN, which is managed by SOMD, has been critical for returning all science data from Mars, a major engineering accomplishment. Looking to next-generation sensors at Mars, and in support of emerging small mission concepts, returning significantly higher volumes of data will be needed. MEP and SOMD are already exploring creative options to enable such growth in data return. SOMD was the first to explore commercial services to the ISS. MEP is already working with its Commercial Division to gain insights from their expertise on the potential of commercial services for Mars exploration.

STMD

Space Technology Mission Directorate

STMD plays a critical Agency-wide role in developing transformative technologies for space exploration. MEP also strives to demonstrate potentially high-payoff technologies before applying them as enablers for subsequent missions. One successful example of a jointly funded STMD and MEP collaboration is the MSL Entry, Descent, and Landing Instrumentation (MEDLI) project. Flown on the MSL heat shield, MEDLI collected data on atmospheric density, aerothermal environments, and subsurface heat shield material response to benefit Mars 2020 and future Mars EDL designs and operations. Through its relationship with STMD, MEP can apply lessons learned and data returned from earlier missions to benefit future missions. Within this 20-year strategy of more frequent Mars missions, MEP can provide increased opportunities to demonstrate STMD-developed technologies in situ, while those STMD technologies can help MEP obtain more performance from their systems.

3.4.2 *Involvement of Diverse Communities*

> *Involve Diverse Communities in Planning and Achieving Mars Exploration for Humanity.*

Per NASA Science Strategy 4.1 (2023 version), SMD seeks “to increase the diversity of thought and backgrounds represented across the entire SMD portfolio through a more inclusive, equitable, and accessible environment.” In doing so, SMD uses a deliberate and measured approach to inclusion, diversity, equity, and accessibility (IDEA)[1] for teams both internal and external to NASA. Mars exploration belongs to all and stands to benefit significantly from contributions by individuals with diverse backgrounds, capabilities, and perspectives. With the guidance of DEIA leaders, MEP will invest in the following types of activities to provide expanded and equitable opportunities to join Mars exploration activities, to make significant mission contributions, and to develop professional expertise and leadership.

Inclusive Leadership and DEIA in MEP

For DEIA, MEP recognizes the critical importance of involving historically excluded communities (HECs) at all stages. Expanded participation of representatives from HECs is sought and valued, particularly in early planning, in alignment with SMD’s IDEA Strategy (“ensure NASA’s goal of building inclusive teams by reflecting the nation in discovery, exploration, and innovation”). The implementation of this MEP 2024–2044 Plan will include collaborative opportunities for these communities to offer principled recommendations that can

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[1] In this MEP Plan, IDEA refers specifically to the SMD strategy, which is “informed by agency-level DEIA strategic goals and is aligned with broader agency plans,” as described on page 29 of the strategy document itself.

In partnership with NASA educational programs, MEP can provide experiences that engage the ideas and talents of a broader pool of future explorers who bring diverse perspectives, backgrounds, and experiences that inspire innovation in the exploration of Mars by all and for all.

guide substantive actions. Recognizing that an inclusive and respectful culture is the cornerstone of any diverse and successful organization, MEP will appoint a staff member to lead the organization of these efforts, apply Agency/Program/Center resources, and demonstrate accountability for MEP DEIA improvements. MEP will work with NASA HQ and Centers, as well as university and industry partners, to support data-driven methods aimed at increasing measurable participation by members of HECs.

Internships, Fellowships, and Leadership Training

The development of internships, fellowships, and leadership training for U.S. persons is crucial to overcoming traditional barriers to entry and retention for HECs in Mars exploration. MEP will work with minority-serving institutions (MSIs) and other universities to support such opportunities in science and engineering. MEP can also develop closer partnerships with activities such as NASA's Planetary Science Summer School, Mentoring and Opportunities in STEM with Academic Institutions for Community Success (MOSAICS), and PI Launchpad by providing speakers, subject matter experts, and content. To bolster critical skills among students and faculty, MEP will continue to support specialized workshops in data processing, research grants in relevant fields, and lab studies, from examining meteorites to testing Mars-like regolith (Figure 37). By offering such opportunities, MEP can foster access for a new generation of diverse planetary scientists, astrobiologists, engineers, and other relevant career professionals, thus enriching the community with a multitude of perspectives and ensuring the next generation of U.S. leadership in Mars exploration.

Figure 37. Next-generation opportunities. Community-college students engage in designing miniature rovers through the NASA Community College Aerospace Scholars (NCAS) program. *NASA/JPL-Caltech/Kim Orr*

Inclusivity in Mars Mission Teams

MEP is dedicated to nurturing and supporting the active engagement of HEC students and faculty in mission-critical roles. Such opportunities include participation in mission proposals and scientist programs by encouraging diverse representation and participation and by fostering inclusive team and work environments. This commitment to inclusivity strengthens the scientific and engineering process by incorporating diverse viewpoints and enabling psychological safety among all team members, thus fostering innovative thinking and comprehensive problem solving. Such measures are essential for engaging the full breadth of human intellectual capacity in exploring Mars. Most recently, both the MSL and Mars 2020 mission teams have participated in NASA’s PSD Here to Observe (H2O) Program, which provides an opportunity for undergraduate students from non-Research-1 (non-R1) institutions (see glossary) to observe PSD mission meetings and activities during the academic year.

MEP will cultivate a work environment that encourages collaboration, flexibility, impartiality, and fairness to enable individuals to contribute to their full potentials and to increase their participation. MEP will seek advice from the SMD Inclusion Plan Community of Practice on best practices for cultivating and sustaining inclusive teams.

Enhanced Professional Participation

Facilitated by conferences, symposiums, and workshops, a key aspect of scientific advancement is the exchange of ideas. By expanding travel stipends for HECs, hosting meetings at MSIs, and co-locating workshops with affinity-group annual meetings, MEP will underscore its commitment to broadening these critical conversations, ensuring they are truly representative of the diversity of thought within Mars-community disciplines.

Partnerships with Educational and Mentorship Programs

NASA’s Agency-wide Equity Action Plan (2023) illustrates why it is important to encourage the participation of academic institutions serving underrepresented and historically excluded groups through active outreach to both MSIs and professional organizations. MSIs include Historically Black Colleges and Universities (HBCUs) and Hispanic-Serving Institutions (HSI). Professional organizations include the Society of Women Engineers (SWE), the National Society of Black Physicists (NSBP), and the Society for Advancement of Chicanos/Hispanics & Native Americans in Science (SACNAS). To nurture a diverse pool of future explorers, MEP is also dedicated to collaborations with industry, academia, and local community organizations that inspire interest and engagement in planetary science among underrepresented participants.

MEP will also seek opportunities to leverage MOSAICS. Formerly known as the NASA SMD Bridge Program, MOSAICS is a new initiative to improve DEIA within the NASA workforce and the broader U.S. science and engineering communities.

3.4.3 *Enhancements to the State of the Profession*

> *Train, sustain, and retain a diverse workforce and maintain an inclusive and respectful workplace.*

Workforce-Needs Analysis

As the science and engineering landscape evolves, understanding workforce requirements is paramount. MEP is dedicated to frequent and thorough workforce analyses, which will be developed as part of the next phase of implementing this Plan. Such analyses will ensure that MEP and the broader Mars community possess the necessary skill sets for addressing the challenges and opportunities of future Mars missions.

Attraction and Retention of Early Career Professionals

The future of Mars exploration depends on fresh ideas and perspectives from early career scientists and engineers. To attract and retain these individuals, MEP seeks to offer appealing opportunities, such as involvement in cutting-edge research projects. Key to a diverse workforce is an unbiased recruitment process, which will be developed in implementing this Plan. In alignment with NASA and Center policies and practices, MEP affirms its commitment to diversity by ensuring equitable recruitment practices that consciously seek out and include talented individuals from HECs and elsewhere. Personalized guidance and support are instrumental in professional growth, particularly for those who might lack disciplinary role models. In partnership with participating universities, MEP can bridge this gap through Agency/Center mentorship programs that create opportunities for meaningful interactions and growth. MEP will actively work toward turning these aspirational goals into reality at the earliest stages of implementing this Plan.

Strategic Partnerships for Workforce Capability Development

MEP supports alliances with industry and academia that offer unique opportunities for students and researchers to gain hands-on experience and develop specific science and engineering expertise.

Workplace Policies

NASA defines *inclusion* as “the full participation, belonging, and contribution of organizations and individuals,” per the NASA Policy Statement on Diversity, Equity, Inclusion, and Accessibility for NASA’s Workforce and Workplaces (2023). An inclusive work environment is one that promotes cultural intelligence (the desire to gain the knowledge, skills, and confidence to interact comfortably with others different than oneself) and psychological safety (where all team members feel safe to belong, learn, contribute, and challenge). Inclusive workplace policies are crucial in creating an environment that respects and values diversity. In alignment with Agency and Center policies, MEP will demonstrate commitment to a supportive work environment through active attention to DEIA best practices and workplace codes of conduct.

3.4.4 *Opportunities for Public Participation in Mars Exploration*

> *Enable direct participation of diverse communities in Mars exploration through a variety of innovative technologies, partnerships, and collaborations.*

MEP is one of NASA’s signature efforts to understand our solar system. Mars missions extend humankind’s virtual presence via robotic explorers in preparation for their eventual human counterparts. Such a compelling endeavor as Mars exploration deserves equally forward-looking initiatives to engage the public in scientific discovery and technological achievements related to Mars. A guiding principle for Mars public engagement is to be as daring, wise, and pathfinding in communication efforts as the Program in designing ambitious, yet achievable, missions. The ongoing vision is *Sharing the Adventure* and *Making Mars a Real Place*, with direct and virtual experiences that transform Mars from an object studied to a knowable destination, first for robotic spacecraft and soon for humans.

Just as Mars missions have been organized into a program where each element strategically complements and builds on another, Mars public engagement is conducted at the program level, covering all constituent Mars missions. This organization prevents the need to reinvent the wheel with each mission, allows continuity beyond the official end dates of missions, and provides the ability to develop strong, stable, long-lasting infrastructure with long-term partners—resulting in greater leverage of partnerships, cost savings, and higher impact with participants (Figure 38).

Figure 38. MEP public engagement extends Mars exploration. *NASA/JPL-Caltech*

As MEP reaches out to Mars, it also reaches across the nation,
creating opportunities for families and communities to
experience discovery and innovation as it happens.

Mars public engagement activities over the next two decades will create greater means for direct public involvement in the mission experiences, including:

- high-definition visualizations and immersive experiences for online platforms, museums, classrooms, and other places of public gathering;
- real-time opportunities for direct public interactions with Mars experts and career role models;
- continuous infusion of new and effective ideas from diverse sources in programming;
- strong networks and infrastructure to increase the dissemination and accessibility of Mars visualizations, immersive experiences, and participative opportunities for diverse audiences around the world;
- inclusion of potential public engagement payloads and related opportunities (e.g., cameras and other experiential software and hardware) early in the development of missions and throughout implementation; and
- integration of Mars science with other areas of knowledge that together make an enriching and compelling human experience.

3.4.5 *Respectful Role in the Stewardship of Mars*

> *Be mindful of responsibilities in exploring Mars "for all humanity."*

With a nearly 60-year history of leadership in Mars exploration, NASA has had a special role in the co-creation of a shared world culture of Mars exploration, with open scientific discovery and technological feats benefitting science at Mars and society on Earth. Generating knowledge of the universe and our place within it is a wholly human endeavor, shared by countless generations through time and across the globe. Future generations hundreds of years from now will look back on this time of early Mars exploration and remember us not only for our achievements but also for the way in which we made history.

Modern Mars exploration is part of our legacy to the future, with the potential to detect life beyond Earth and a time to take the next leap of establishing a human presence on a neighboring world. Stewardship of Mars is an inherently global endeavor, yet MEP has a leading role that includes commitment to the following:

- informed, planetary protection of Mars and Earth;
- environmental science that reduces both impacts to the local Martian environment and impacts of the Martian environment on human explorers;
- preservation of unique geologic features and settings;
- thoughtful, ethical, and sustainable use and reuse of Martian resources;
- opportunities to address cultural values and to understand sensitivities;
- maximizing scientific and technological benefits for all; and
- balancing shared access and the continued peaceful exploration of space.

A stewardship role centers on a spirit of cooperation. It supports international treaties that promote harmony in human-robotic pursuits in the Martian system. It also emphasizes a model of scientific discovery and community as the driving impetus, akin to establishing research stations in Antarctica for peaceful purposes. A stewardship role also requires consideration of environmental monitoring, long-term planning, forethought in remediation, and sustainability. These practices are not only good for the planet but also necessary for ensuring safer and more long-lasting human habitation zones where future explorers will one day live and work.

Stewardship of Mars is our legacy to future generations of explorers and honors the peaceful exploration of space in our times.

By exploring Mars together, we can pursue knowledge for humanity, building a culture of cooperation for our soon-to-be home on a neighboring world.

NASA leadership in the stewardship of Mars also recognizes that exploring Mars “for all humanity” does not presume that Earth’s peoples monolithically share the same exploration philosophies and welcomes genuine, intellectual collaboration across cultures, organizations, and entities. MEP will thus engage in perspective-taking activities to consider and honor, to the greatest extent possible, what is important to diverse peoples in the nation and around the world, as well as to nongovernmental commercial, university, and nonprofit organizations with vested interests and increasing capabilities in Mars exploration. The goal of this initiative is to continue to inspire not only through profound discoveries and cutting-edge innovations but also through ethical conduct that serves and preserves diverse, intergenerational interests, values, and opportunities in interplanetary peace and prosperity.

> *"NASA has been ever present at Mars for almost 60 years, and we are excited about a sustainable, consistent, and stable science presence at the Red Planet for the next two decades and beyond. By working with the large variety of mission types, interested partners, and new technologies, NASA will be able to continue its role leading the world in pursuit of robotic exploration of this amazing, dynamic planet."*

Dr. Lori Glaze
Deputy Associate Administrator,
Exploration Systems Development Mission Directorate

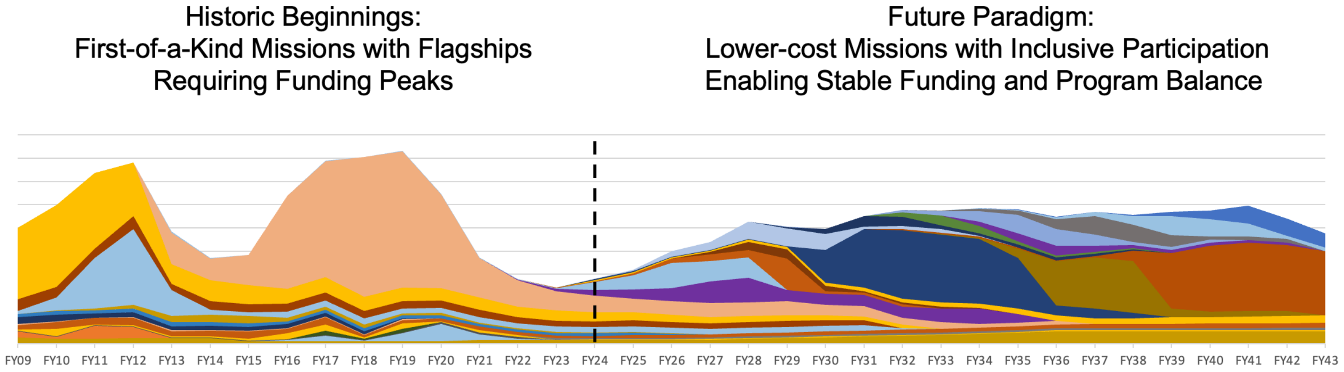
Artist's concept. *NASA*

4 PROGRAM ARCHITECTURE CONCEPT

> By building infrastructure, developing mission-enabling technologies, and engaging in other cost-reducing partnership opportunities, MEP can maintain a balanced program of lower-cost, high-cadence, medium-class missions; missions of opportunity; and inclusive initiatives that strengthen the science and engineering community and the ability of the worldwide public to participate in the discovery of this age.

The architecture of this MEP 2024–2044 Plan is driven by science—the science MEP seeks to achieve on behalf of the nation and all activities that enable it: the infrastructure to get to Mars and support missions once they are there, technology investments that improve the capability of missions and open new destinations to explore at the surface and in the subsurface and atmosphere of Mars, and engagement of a broader Mars community. Success of the program depends on understanding not only the state of Mars exploration today but also where it may be heading. International collaboration has always been an important element of individual MEP missions, yet accomplishments by both experienced and emerging space agencies suggest that the world is on a path toward a global consortium of Mars science explorers. Similarly, the commercial space sector has seen exponential growth in recent years. While most of the commercial interest is currently focused on Earth and the Moon, Mars is increasingly a target for private industry. It is incumbent on MEP to be a leader in demonstrating how public-private partnerships can be implemented for mutual benefit.

Another important element of the architecture is to have a sustainable program (Figure 39). MEP’s traditional model of large, multi-instrument flagship missions have produced spectacular science, but they are programmatically challenging to implement. The typical funding profile of these missions includes large spikes in funding requirements between the preliminary design phase and launch. Technical challenges in mission development cause these spikes to grow



MEP Annual FY Budget (FY09-FY24) and Sample Future Budget Profile* (FY24 – FY2044) based on MEP 2024 – 2044 Plan "Exploring Mars Together"
*Deliberately flexible among the plan's initiatives, depending on discoveries, capabilities, priorities, and budget availability

Figure 39. Concept for a balanced, flexible, stable, and sustainable MEP budget profile. This figure depicts historical funding levels as compared to a notional sustained budget.

and/or ramp down slower. Inflation, supply-chain issues, and inadequate vendor bases also contribute to funding challenges.

MEP's historical top-level funding has resulted in a series of budget peaks and valleys corresponding to large-mission development cycles. This volatility in funding requirements creates challenges for MEP sponsors in the executive and legislative branches of government. It can also impact NASA's overall PSD portfolio, as the PSD budget is relatively stable on a year-to-year basis. A shift away from large, multi-billion-dollar missions to both lower-cost ($100M–$300M), competitively selected missions and medium-class (under $2B) strategic missions enables the establishment of a sustainable MEP program-level budget with science and other exploration opportunities for more participants. Table 1 outlines high-level budget elements enabling a stable plan.

The timing for implementation of this MEP 2024–2044 Plan depends on the prioritization of the activities in the Plan's initiatives relative to other elements of the PSD portfolio, including MSR. Realistically, this Plan would not be fully realized until after MSR has returned samples to Earth. However, the agile nature of the architecture provides the flexibility to implement portions of the Plan significantly sooner if funding were available. This detailed Plan allows MEP to advocate within NASA, SMD, and PSD, as well as to inform external stakeholders and partners about where investment can realize the best progress on specific parts of the Plan and overall. MEP must adapt both to the new budget environment and to the new opportunities. Together, we can do that, moving forward to expand the successful exploration of our nearest habitable planetary neighbor, Mars.

Table 1. MEP Budget Planning Elements

High-level Budget Planning Elements Consistent with this MEP 2024–2044 Plan

EXISTING COMMITMENTS

Budget Planning Element 1—Program of Record

Continue to operate existing missions in MEP’s portfolio, which include 2001 *Mars Odyssey*, MRO, MSL (Mars rover *Curiosity*), MAVEN, and Mars 2020 (Mars rover *Perseverance*). These missions continue to provide rich Mars data, with the two orbiters additionally contributing essential relay for the surface assets.

MEP will support the current NASA contributions to ESA’s Rosalind Franklin Mission. MEP will also implement the SRP, which includes all Earth ground elements for the MSR samples, including an SRF; SRP activities will be aligned with MSR planning.

INITIATIVE 1

Budget Planning Element 2—Lower-Cost, High-Cadence Missions

Solicit for lower-cost science missions in the $100M–$300M range* as a new element in the MEP mission portfolio, offering frequent (every launch opportunity) and affordable opportunities for Mars exploration and the possibility of networked and/or coordinated observations.

Budget Planning Element 3—Medium-Class Strategic Missions

Develop medium-class missions that are responsive to the decadal survey (OWL, 2023) science recommendations. These missions would be launched notionally once per decade, scaled appropriately for the targeted science, and budgeted not to exceed $2B.

Budget Planning Element 4—Missions of Opportunity

Partner in international and/or commercial missions to advance high-value science and to develop infrastructure through payloads and other contributions, while reducing costs and risks through the shared activities.

INITIATIVE 2

Budget Planning Element 5—Infrastructure Investments

Enable infrastructure advancements to benefit multiple Mars missions. These may include access to Mars (e.g., delivery systems) and mission support (e.g., telecommunications relay support, high-resolution imaging, and global weather monitoring).

INITIATIVE 3

Budget Planning Element 6—Technology Investments

Invest in technologies supporting areas such as EDL, autonomy, mobility, and drilling that may enable future missions.

INITIATIVE 4

Budget Planning Element 7—Mars Community Development

Implement programmatic activities that build a more diverse and inclusive Mars community, including developing partnerships, enhancing the state of the profession, enabling public engagement, and stewardship.

* Excluding launch vehicle and Phase E operations

APPENDICES

A. ACRONYMS

AMASE	Artic Mars Analog Svalbard Expeditions
AO	Announcement of Opportunity
APXS	Alpha Proton X-Ray Spectrometer
ARADS	Atacama Rover Astrobiology Drilling Studies
ARMD	Aeronautics Research Mission Directorate
BRAILLE	Biologic and Resource Analog Investigations in Low Light Environments
CaSSIS	Colour and Stereo Surface Imaging System
ChemCam	Chemistry and Camera
CLPS	Commercial Lunar Payload Services
COTS	Commercial Orbital Transportation Services
DEIA	Diversity, Equity, Inclusion, and Accessibility
DSN	Deep Space Network
DTE	direct to earth
EDL	entry, descent, and landing
EELV	Evolved Expendable Launch Vehicle
ESA	European Space Agency
ESCAPADE	Escape and Plasma Acceleration and Dynamics Explorers
ESDMD	Exploration Systems Development Mission Directorate
ESPA	Evolved Expendable Launch Vehicle Secondary Payload Adapter
EXO	Exobiology
GITL	ground-in-the-loop
GNC	guidance, navigation, and control

H2O	Here to Observe
HBCUs	Historically Black Colleges and Universities
HECs	historically excluded communities
HiRISE	High Resolution Imaging Science Experiment
HIS	Hispanic-Serving Institutions
HPSC	High Performance Space Computing
HW	Habitable Worlds
IMEWG	International Mars Exploration Working Group
I-MIM MDT	International Mars Ice Mapper Measurement Definition Team
IMRCWG	International Mars Relay Coordination Working Group
IOAG	Interagency Operations Advisory Group
IR	infrared
ISECG	International Space Exploration Coordination Group
ISRU	in situ resource utilization
JMARS	Java Mission-planning and Analysis for Remote Sensing
KISS	Keck Institute for Space Studies
KISS RAMS	Keck Institute for Space Studies Revolutionizing Access to the Mars Surface
M2020	Mars 2020
M2M	Moon to Mars
MarCO	Mars Cube One
MASWG	Mars Architecture Strategy Working Group
MatISSE	Maturation of Instruments for Solar System Exploration
MAVEN	Mars Atmosphere and Volatile EvolutioN
MCE-SAG	Mars Concurrent Exploration Science Analysis Group
MDAP	Mars Data Analysis Program

MEDA	Mars Environmental Dynamics Analyzer
MEDLI	Mars Science Laboratory Entry, Descent, and Landing Instrumentation
MEPAG	Mars Exploration Program Analysis Group
MGS	Mars Global Surveyor
MLE	Mars Life Explorer
MMGIS	Multi-Mission Geographical Information System
MO&DA	Mission Operations and Data Analysis
MOMA	Mars Organic Molecule Analyzer
MOMA-MS	Mars Organic Molecule Analyzer Mass Spectrometer
MRN	Mars Relay Network
MRO	Mars Reconnaissance Orbiter
MSIs	minority-serving institutions
MSL	Mars Science Laboratory
MSPA	multiple spacecraft per aperture
MSR	Mars Sample Return
NAIF	Navigation and Ancillary Information Facility
NMs	NASA Models
NOMAD	Nadir and Occultation for MArs Discovery
NSBP	National Society of Black Physicists
ODY	Odyssey
OWL	Origins, Worlds, and Life
PDS	Planetary Data System
PHX	Mars Phoenix Lander
PI	Principal Investigator
PICASSO	Planetary Instrument Concepts for the Advancement of Solar System Observations

PIXL	Planetary Instrument for X-ray Lithochemistry
PNT	positioning, navigation, and timing
PSD	Planetary Science Division
PSPs	Participating Scientist Programs
PSTAR	Planetary Science Technology Analog Research
R&A	Research & Analysis [Mars R&A and Planetary Science R&A]
R1	Research-1 [institutions]
REMS	Rover Environmental Monitor Station
RFM	Rosalind Franklin Mission
RIMFAX	Radar Imager for Mars’ Subsurface Experiment
SACNAS	Society for Advancement of Chicanos/Hispanics & Native Americans in Science
SAM	Sample Analysis at Mars
SCaN	Space Communications and Navigation
SHARAD	SHAllow RADar
SMD	Science Mission Directorate
SOMD	Space Operations Mission Directorate
SPA	Secondary Payload Adapter
SRF	Sample Receiving Facility
SRP	Sample Receiving Project
SSW	Solar System Workings
STEM	science, technology, engineering, and mathematics
STMD	Space Technology Mission Directorate
SWaP	size, weight, and power
SWE	Society of Women Engineers
SWIM	subsurface water ice mapping

TGO	Trace Gas Orbiter
UAE	United Arab Emirate
UHF	ultra-high frequency
UV	ultraviolet
UV-Vis-NIR	ultraviolet–visible–near infrared

B. GLOSSARY OF KEY TERMS

The following definitions apply to this MEP 2024–2044 Plan and thus may differ in moderation from those used in other contexts, both internal and external to NASA.

Mars: encompasses the Martian system, inclusive of its two moons, Phobos and Deimos.

Medium-Class Strategic Mission: is between approximately \$1–\$2B, exclusive of the launch vehicle and mission operations (i.e., Phase E–F costs); for reference, the OWL (2023) recommendation for a New Frontiers mission cost cap was \$1.65B, as compared to the 2024 NASA \$900M cost cap.

Lower-Cost Mission: is approximately \$100–300M, exclusive of the launch vehicle and mission operations (i.e., Phase E–F costs); for reference, the OWL (2023) recommendation for a Discovery mission cost cap was \$800M, as compared to the 2024 NASA \$500M cost cap.

Mission of Opportunity: is a previously unplanned opportunity to fly an instrument or spacecraft in tandem with one or more organization’s mission assets (e.g., an invitation to or from NASA to manifest a payload on a spacecraft, launch vehicle, or delivery system).

Public-Private Partnership: is a joint effort between NASA and one or more industry or other private-sector partners in which resources, technical capabilities, and risks are shared to develop mutually beneficial products and services, often in less time and at lower cost than otherwise possible; typically enabled by a Space Act Agreement (SAA) executed under NASA’s Other Transactional Authority (OTA), which is designed to allow the advancement of capabilities that, once developed, can later be procured through traditional contracts.

R1 Institutions: per the Carnegie Classification of Institution of Higher Education, are universities with high research activities (\$50M+ in research, 70+ research doctorates/year).

C. ALIGNMENTS WITH GUIDING DOCUMENTS

MEP 2024 – 2044 PLAN		INPUTS TO THE PLAN									
		OWL	MEPAG	MASWG	MCE-SAG	KISS-RAMS	LCSMC	MEPIND	IMIM-MDT	M2M	NM
	PROGRAM SCIENCE THEMES										
SCI 1	EXPLORING THE POTENTIAL FOR MARTIAN LIFE	●	●	●	●	●			●	●	
SCI 2	SUPPORTING THE HUMAN EXPLORATION OF MARS	●	●	●		●			●	●	
SCI 3	REVEALING MARS AS A DYNAMIC PLANETARY SYSTEM	●	●	●	●	●	●		●	●	
	PROGRAM OF RECORD	●	●								
	NEW MEP INITIATIVES										
NMI 1	EXPANDED MISSION OPPORTUNITIES										
1.1	Lower-cost Missions	●		●	●	●	●	●			
1.2	Medium-class Strategic Missions	●		●		●		●	●		
1.3	Missions of Opportunity	●		●	●	●		●	●		
NMI 2	**INFRASTRUCTURE INVESTMENTS**										
2.1	Mars Relay Network	●		●	●	●	●	●	●	●	
2.2	Spacecraft Delivery and Payload Hosting				●	●	●	●	●	●	
2.3	High-resolution Imaging						●	●	●	○	
2.4	Weather Monitoring & Prediction							●	●	○	
2.5	Ground Receiving Networks	●								●	
2.6	Data Infrastructure, Visualization, & Analysis	●		●					●		
NMI 3	**TECHNOLOGY INVESTMENTS**										
3.1	Entry, Descent, & Landing	●			●	●	●			○	
3.2	Surface and Aerial Mobility	●		●	●	●	●			○	
3.3	Avionics, Autonomy, & Power	●			●	●				○	
3.4	Drilling & Sample Handling	●		●	●	●				○	
3.5	Mars Science Instruments	●		●	●	●	●		●	●	
3.6	Telecommunications	●		●	●	●	●		●	●	
NMI 4	**MARS COMMUNITY**										
4.1	Mission-enabling Partnerships (International, Commercial, Academic etc.)	●		●	●	●	●	●	●	●	●
4.2	Involvement of Diverse Communities	●				●		●	●		
4.3	Enhancements to the State of the Profession	●				●					
4.4	Opportunities in Public Engagement & Participation in Mars Exploration	●				●					
4.5	Respectful Role in the Stewardship of Mars	●			●					●	

INPUT ALIGNMENTS, IN BRIEF

SCI 1 LIFE

OWL	CHAPTER 9 INSIGHTS FROM TERRESTRIAL LIFE | CHAPTER 10 DYNAMIC HABITABILITY | CHAPTER 11 SEARCH FOR LIFE ELSEWHERE | *Contributions to:* CHAPTER 12 EXOPLANETS
MEPAG	Goal 1 (Life)
MASWG	Diverse habitable environments; Subsurface structure, composition, and life/organics detection in ice
MCE-SAG	Dynamic Mars: Early environmental change, modern habitability; Planetary protection
KISS-RAMS	Surface missions for habitability and life detection
I-MIM MDT	Habitability and ice-mapping for future surface life-detection mission(s) and human mission(s), including assessments for surface science, ISRU, landing/launch, and civil engineering
M2M	LUNAR/PLANETARY SCIENCE (LPS-4M)

SCI 2 HUMANS

OWL	CHAPTER 19 HUMAN EXPLORATION (Pivotal role of science in driving/implementing human exploration, in situ resource utilization) | CHAPTER 21 TECHNOLOGY (ISRU) | CHAPTER 22: RECOMMENDED PROGRAM (Transformative Science Enabled by a Synergistic Robotic-Human Partnership)
MEPAG	Goal 4 (Human Prep) and Goals 1-3 (Life, Climate, Geology) for science a human presence would further enable
MASWG	Collaboration with human-mission planners for complementary science (dust cycle, lower latitude ice deposits) and to define needs
KISS-RAMS	Surface missions for human exploration goals
I-MIM MDT	Characterizing candidate sites for human-enabled surface science, ISRU and civil engineering; atmospheric studies for EDL and surface operations
M2M	LUNAR/PLANETARY SCIENCE (LPS-1M) | SCIENCE-ENABLING (SE-5M, SE-6M) | APPLIED SCIENCE (AS-1M, AS-2M, AS-3M) | *Robotic data /infrastructure/technology contributions to:* HUMAN/BIOLOGICAL SCIENCES (HBS-1M, HBS-2M, HBS-3M) | SCIENCE ENABLING E-3M, SE-4M) | APPLIED SCIENCE (AS-4M, AS-5M, AS-6M) OPERATIONS (OP-2M, OP-3M, OP-4M, OP-5M, OP-8M, OP9M, OP10M, OP11M, OP12M)

SCI 3 SYSTEMS

OWL	CHAPTER 3 ORIGIN OF EARTH & INNER SOLAR SYSTEM BODIES | CHAPTER 4 IMPACTS & DYNAMICS | CHAPTER 5 SOLID BODY INTERIORS AND SURFACES | CHAPTER 6 SOLID BODY ATMOSPHERES, MAGNETOSPHERES, & CLIMATE EVOLUTION | *Contributions to:* Chapter 12 EXOPLANETS
MEP	Goals 1-4 (Life, Climate, Geology, Human Prep)
MASWG	Recent climate change as recorded in the ice; Climate variability and process
MCE-SAG	Dynamic Mars: planetary evolution, early environmental change, recent climate evolution, dynamic modern environments
KISS-RAMS	Surface missions for understanding the long-term evolution of Mars

LCSMC	Atmospheric Science, Crustal Magnetism, Geology, Geodesy, Habitability, High-Res IR Imaging, Seismology, Space Weather, Subsurface Ice Deposits
I-MIM MDT	Ancient and modern systems science (Atmospheric Science, Climatology, Geology, Habitability)
M2M	LUNAR/PLANETARY SCIENCE (LPS-1M, LPS-2M, LPS-3M) | *Contributions to:* Heliophysics Science (HS-1M, HS-2M, HS-3M, HS-4M)

PROGRAM OF RECORD

OWL	CHAPTER 20 INFRASTRUCTURE (Sample Curation Facilities) | CHAPTER 22 RECOMMENDED PROGRAM (ongoing missions and existing programs)

NMI 1 MISSIONS

OWL	CHAPTER 22 RECOMMENDED PROGRAM (balance
MASWG	Lower-cost missions (PI-led); medium-class missions (more capable for most challenging science objectives); missions of opportunity (participation in non-NASA missions)
MCE-SAG	Lower-cost missions (accomplishable science and business strategies)
KISS-RAMS	Lower-cost missions, occasional larger strategic missions, missions of opportunity
LCSMC	Regular cadence, low-cost missions
MEPIND	Lower-cost commercial services: delivery and payload hosting (large and small); next-generation telecommunications; high-resolution imaging, next-generation meteorology
I-MIM MDT	Lower-cost mission (commercial/international)
M2M	RECURRING TENETS (RT-1, RT-2) | SCIENCE-ENABLING (SE-5M, SE-6M) | APPLIED SCIENCE (AS-2M, AS-3M) MARS INFRASTRUCTURE (MI-4M)

NMI 2 INFRASTRUCTURE

OWL	CHAPTER 20 INFRASTRUCTURE (Data archiving/distribution, deep-space communications/navigation, Deep Space Network) | CHAPTER 21 TECHNOLOGY (Communications systems)
MCE-SAG	Delivery (to orbit and surface); telecommunications
KISS-RAMS	Launch/delivery capabilities; telecommunications
LCSMC	Next-generation telecommunications and transportation (Mars Tug)
MEPIND	Delivery and payload hosting (large and small), telecommunications, high-resolution imaging
I-MIM MDT	Next-generation telecommunications and high-resolution imaging
NM:	Commercial services models (CLPS, COTS, etc.)
M2M	MARS INFRASTRUCTURE (Telecommunications/PNT-related: MI-2M, MI-3M) | OPERATIONS (Telecommunications-related: OP-2M, OP-4M) | TRANSPORTATION/HABITATION (Delivery-related: TH-5M, TH-6M, TH-12M)

NMI 3 TECHNOLOGY

OWL	CHAPTER 21 TECHNOLOGY (aerial/surface mobility, autonomy, challenging environments, communications systems, power, planetary protection, sample processing, science instruments, subsurface access)
MASWG	Competed technology development to advance instrumentation and small spacecraft technologies; mobility, ice mapping and sampling
MCE-SAG	Aerial/Surface Mobility/Manipulation, Autonomy, Avionics, Computing, Power, Science Instruments (lower mass), Subsurface Access (Drilling)
KISS-RAMS	Aerial/ Surface Mobility/Manipulation, Autonomous Systems, EDL, Electronics, Flight System Testing, Landers, Networks, Science Instruments, Software
LCSMC	Aerial/ Surface Mobility/Manipulation, Commercial-off-the-Shelf Architecture, EDL, HPC & Autonomy, Miniaturized science Instruments
IMIM-MDT	Telecommunications, Science instruments
M2M	*Contributions to human-class systems*: Power (MI-1M) | ISRU (MI-4M, OP-3M, OP-11M, OP-12M) | Mobility (OP-5M) | Reuse (OP-8M, OP-11M) | Systems/Instruments for Scientific Discovery (TH-8M, TH-10M) | Telecommunications (OP-4M)

NMI 4 PARTICIPATION

OWL	PARTNERSHIPS CHAPTER 1 (International) | CHAPTER 19 (Commercial/International) | CHAPTER 21: (Commercial) STATE OF THE PROFESSION | DIVERSITY | PUBLIC ENGAGEMENT: *All in* CHAPTER 16 STATE OF THE PROFESSION STEWARDSHIP CHAPTER 19 : HUMAN EXPLORATION (ethical/responsible ISRU) | CHAPTER 21 TECHNOLOGY (planetary protection)
MASWG	PARTNERSHIPS Commercial/International; NM (e.g., CLPS)
MCE-SAG	PARTNERSHIPS Commercial | STEWARDSHIP Planetary protection
KISS-RAMS	PARTNERSHIPS Commercial, international (Including emerging space powers), academic & inter-governmental | STATE OF THE PROFESSION (Workforce Development) | DIVERSITY | PUBLIC ENGAGEMENT
LCSMC	PARTNERSHIPS Commercial, international, academic
MEPIND	PARTNERSHIPS Commercial that enables NASA, international, and academic lower-cost missions
I-MIM MDT	PARTNERSHIPS Commercial, international, academic
NM	PARTNERSHIPS Commercial
M2M	PARTNERSHIPS RECURRING TENETS (RT-1; RT-2; RT-9) STEWARDSHIP RECURRING TENETS (RT-6) | SCIENCE-ENABLING (SE-7M) | OPERATIONS (OP-12M)

ALIGNMENT BETWEEN MEP SCIENCE THEMES AND M2M OBJECTIVES

Overall: SE-6M: Long-term, planet-wide scientific research

Crosscutting: International and commercial collaboration (RT-1, RT-2); Sampling of frozen volatiles and site characterization (SE-3^{M} & SE 5^{M}); Responsible use (peaceful purpose and stewardship); and the Preservation & protection of special features (SE-7^{M})

Science Theme 1 (Exploring the Potential for Martian Life) corresponds most closely with LPS-4^{M} (Life in the Solar System), which is further supported by objectives relating the solar system history, ancient and active processes, Martian volatiles, history recorded in the regolith, the sampling of frozen volatiles, and site characterization (e.g., for astrobiology and climatology potential).

Science Theme 2 (Supporting the Human Exploration of Mars) corresponds most closely with AS-2^{M} (Science to Optimize Human Campaigns), as supported by characterization of environments for life-support design (AS-3^{M}), Mars environmental hazards (HBS-1^{M}), accessible resource characterization (OP-3^{M}), command and control processes for science ops (OP-4^{M}), ISRU regolith demonstrations (OP-11^{M}), Mars environmental science for sustainability (OP-12^{M}), crew time science activities (RT-4), mission-specific science training (SE-1^{M}), remote support of astronauts from scientists on Earth (SE-2^{M}), and mission-specific sample science priorities (SE-4^{M}).

Science Theme 3 (Revealing Mars as a Dynamic Planetary System) corresponds most closely with LPS-2^{M} (Ancient & Active Processes), which is further supported by solar system history (LPS-1^{M}), Martian volatiles (LPS-3^{M}), life in the solar system (LPS-4^{M}), space weather (HS-1^{M}), history recorded in the regolith (HS-2^{M}), plasma/dust-plasma processes (HS-3^{M}), solar-wind dynamics (HS-4^{M}), and physical systems and fundamental physics (PPS-2^{M}).

ALIGNMENT BETWEEN MEP INITIATIVES AND M2M OBJECTIVES

Overall: SE-6M: Long-term, planet-wide scientific research

Core Infrastructure Serving All Missions (MEP Initiative 2) aligns with telecommunications (MI-2^{M}), PNT (MI-3^{M}), maintainability and reuse (RT 5), interoperability (RT 7), leverage of low-earth orbit (RT 8), transportation systems for delivery (TH-6^{M}), and cargo mass for science return (TH-12^{M}).

Targeted Mars Technology Development (MEP Initiative 3) aligns with surface power (MI-1^{M}), long-lead ISRU demonstrations (MI-4^{M}), surface mobility systems (OP-5^{M}), ISRU regolith demonstrations (OP-11^{M}), sampling of frozen volatiles (SE-3^{M}), systems for science and resources (Th-6^{M}), and inter-related human-robotic systems for science (TH-10^{M}).

Exploring Mars Together (MEP Initiative 4) aligns with optimization of Earth-Mars team interactions (OP-2^{M}), command and control processes for science operations (OP-4^{M}), crew time for science activities (RT 4), mission-specific science training (SE-1^{M}), remote support of astronauts from scientists on Earth (SE-2^{M}), mission-specific sample science priorities (SE-4^{M}), and preserving and protecting special features SE-7^{M}).

D. MODEL FOR MEP CAPACITY-BUILDING EVALUATION

> By focusing on building and assessing its capacity, MEP seeks to increase individual and organizational effectiveness motivated by its mission, vision, values, and foundational concepts, and initiatives, as well as by new realities posed by the complex and changing environment of Mars exploration.

NASA has a rigorous system for evaluating MEP, including:

- progress toward achieving Agency strategic goals/objectives and NASA science priorities/strategies (e.g., assessed through the Planetary Science Advisory Committee in the annual Government Performance and Results Act review process);
- program-level assessments that ensure program balance and execution of program goals instantiated through NASA program management practices; and
- mission gateway and other reviews that assess project management practices (performing within cost/schedule constraints, risk management, etc.) and mission outcomes vis-à-vis mission success criteria.

The intent of evaluation associated with this plan is not to load on additional requirements and metrics to an already thorough set of program evaluation commitments that are assessed through the above processes. Instead, program evaluation associated with this plan utilizes a capacity-building evaluation framework to complement required NASA institutional assessments.

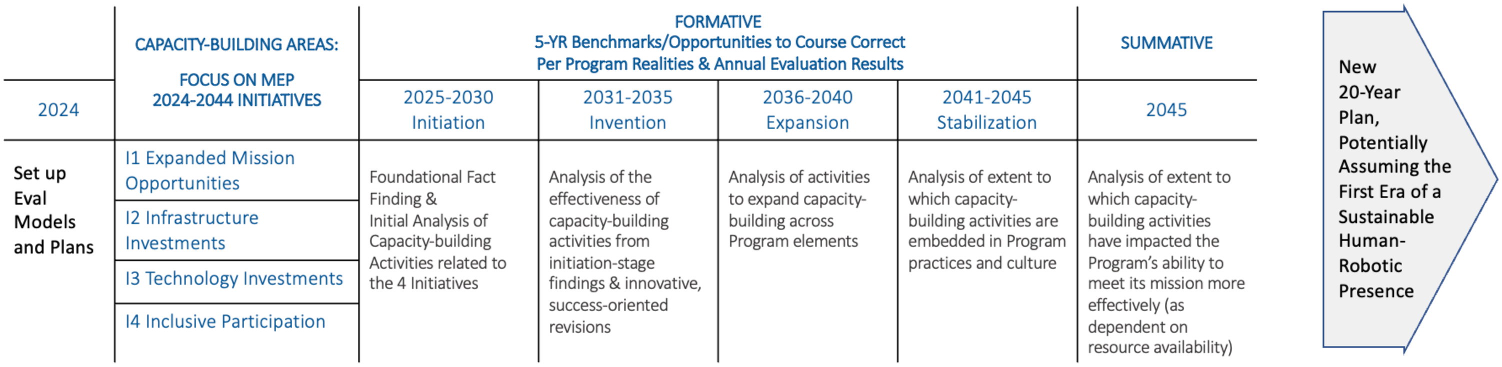
Capacity building is a long-term process of change, with activities designed to increase individual and organizational effectiveness, particularly in complex and ever-changing circumstances. Rather than measuring performance outcomes against requirements, capacity-building evaluation is structured:

- to increase MEP's ability and agility to fulfill its mission (p. xxv);
- to assess active and regular ways to stimulate growth and effectiveness;
- to provide evidence that MEP has contributed to building the overall capacity of NASA as the organization it serves and, by extension, national capacities as well (e.g., U.S. competitiveness in deep space, next-generation workforce, etc.);

- to enhance MEP's ability to strengthen relationships and to mobilize resources; and, importantly,
- to frame MEP's capacity and growth as dependent on resource availability and on other relevant social and organizational contexts so that the expectation and evaluation of measurable progress is reasonable and commensurate with Program scope.

Using participatory evaluation methods, capacity-building assessments intentionally engage MEP stakeholders—internal and external—in assessing desired transformations in which they have a key role, responsibility, and motivation in fulfilling, and places MEP participants as innovators in a shared community of both implementation and evaluation practice. This approach is particularly appropriate given that MEP initiatives emphasize building program capacities through science/technology feed-forward, mission-enabling infrastructure, partnerships, and diversity and inclusion. It also provides organizational supports for MEP and its community of stakeholders through cultural, implementation-oriented, and other changes that stem from the "inflection point" of the changed business and exploration environment detailed in the plan.

MEP will develop a capacity-building evaluation plan with benchmarks in five-year increments over the long-term change process. Since science outcomes are measured through formal NASA processes, the focus of evaluation is on strengthening the means by which MEP and its diverse body of stakeholders can collectively accomplish the four 2024–2044 initiatives. The following diagram provides a notional high-level plan for a long-term programmatic capacity-building evaluation effort. Benchmarks and related phase transitions are scoped in five-year increments. Activities will be structured to advance MEP's ability to fulfill its mission, motivated by its vision, values, and foundational concepts (pp. xxv–xxvii).



	CAPACITY-BUILDING AREAS: FOCUS ON MEP 2024-2044 INITIATIVES	FORMATIVE 5-YR Benchmarks/Opportunities to Course Correct Per Program Realities & Annual Evaluation Results				SUMMATIVE	
2024		2025-2030 Initiation	2031-2035 Invention	2036-2040 Expansion	2041-2045 Stabilization	2045	
Set up Eval Models and Plans	I1 Expanded Mission Opportunities I2 Infrastructure Investments I3 Technology Investments I4 Inclusive Participation	Foundational Fact Finding & Initial Analysis of Capacity-building Activities related to the 4 Initiatives	Analysis of the effectiveness of capacity-building activities from initiation-stage findings & innovative, success-oriented revisions	Analysis of activities to expand capacity-building across Program elements	Analysis of extent to which capacity-building activities are embedded in Program practices and culture	Analysis of extent to which capacity-building activities have impacted the Program's ability to meet its mission more effectively (as dependent on resource availability)	New 20-Year Plan, Potentially Assuming the First Era of a Sustainable Human-Robotic Presence

Figure 40. Notional capacity-building evaluation framework for MEP 2024–2044 Plan. *NASA/MEP*

E. STATUS AND FUTURE WORK

This appendix will provide updates on the progress of the Plan at least annually, within the constraints of MEP's budget profile.

Overview of Near-Term Activities

- Achieve the objectives of the MEP Program of Record, including development of the Sample Receiving Project for the returned Mars samples.
- Collaborate with ESA on the ExoMars Rosalind Franklin Mission.
- Seek low-cost opportunities to address critical infrastructure needs (particularly communications relay and high-resolution imaging).
- Continue investments in key mission-enabling technologies, especially those enabling the search for life and subsurface access.
- Develop public-private partnership arrangements, reinforce existing international partnerships, and explore new opportunities with established and emerging space organizations
- Commission a National Academies study to identify science objectives for human campaigns to Mars.

Commercial Services Study (2024)

This activity is focused on near-term priority infrastructure, including:

- Mars Relay Network (3.2.1),
- Spacecraft Delivery (3.2.2),
- Payload-Hosting Services (3.2.2), and
- High-Resolution Imaging (3.2.3)

The commercial services studies leverage significant prior government-industry investments for Earth and the Moon and—for a comparatively small additional investment—tailor for Mars and the deep-space environment. As part of this activity, MEP competitively selected 12 studies (nine companies) in the four near-term priority infrastructure areas. Interim reports from awardees show promising possibilities in terms of both capabilities and lower costs. Studies additionally provide inputs on needs for a public-private partnership phase. Final reports were submitted in August 2024. MEP will consider follow-on steps based on findings and available budget but is committed to developing collaboration opportunities.

NOTE: This commercial services study is separate from the 2024 released MSR RFP engaging industry in potential solutions for that campaign.

Future Investments in Key Technologies (2024)

The fiscal year 2025 President’s Budget Request included an additional $40M for early investments in Mars exploration technologies. MEP plans for this funding include both directed activities at NASA Centers and competed projects for industry and academia. There was an initial call for technology concepts, which resulted in 90 submissions from six NASA Centers. Approximately 75% of these will be asked to provide expanded proposals in a second round. Science inputs were taken from OWL, MCE-SAG, and the MLE study.

Key Technology Areas Include:

- Entry, Descent, and Landing (3.3.1)
  - Reduce cost of hard and soft landing for more frequent access.
  - Enable landing at higher elevations for wider access.
- Surface and Aerial Mobility (3.3.2)
  - Enable aerial mobility with payload of several kilograms.
  - Access rougher terrain and higher latitudes with surface mobility.
- Avionics, Autonomy, and Power (3.3.3)
  - Revolutionize onboard compute capability and autonomy with less mass, power, and volume.
  - Greatly extend mission duration through power system advances.
- Drilling and Sample Handling (3.3.4)
  - Drill much deeper than 2 meters with affordable mass.
  - Improve planetary protection and bioburden characterization for life detection missions.
- Mars Science Instruments (3.3.5)
  - Mature instruments for: biosignature detection, next-generation remote sensing, and lower-cost landed investigations.
- Telecommunications (3.3.6)

- Enable aerial vehicle communication directly to orbit.
- Greatly expand proximity and DTE communication bandwidth.
- Enable intersatellite communication links for next-generation relay network.

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