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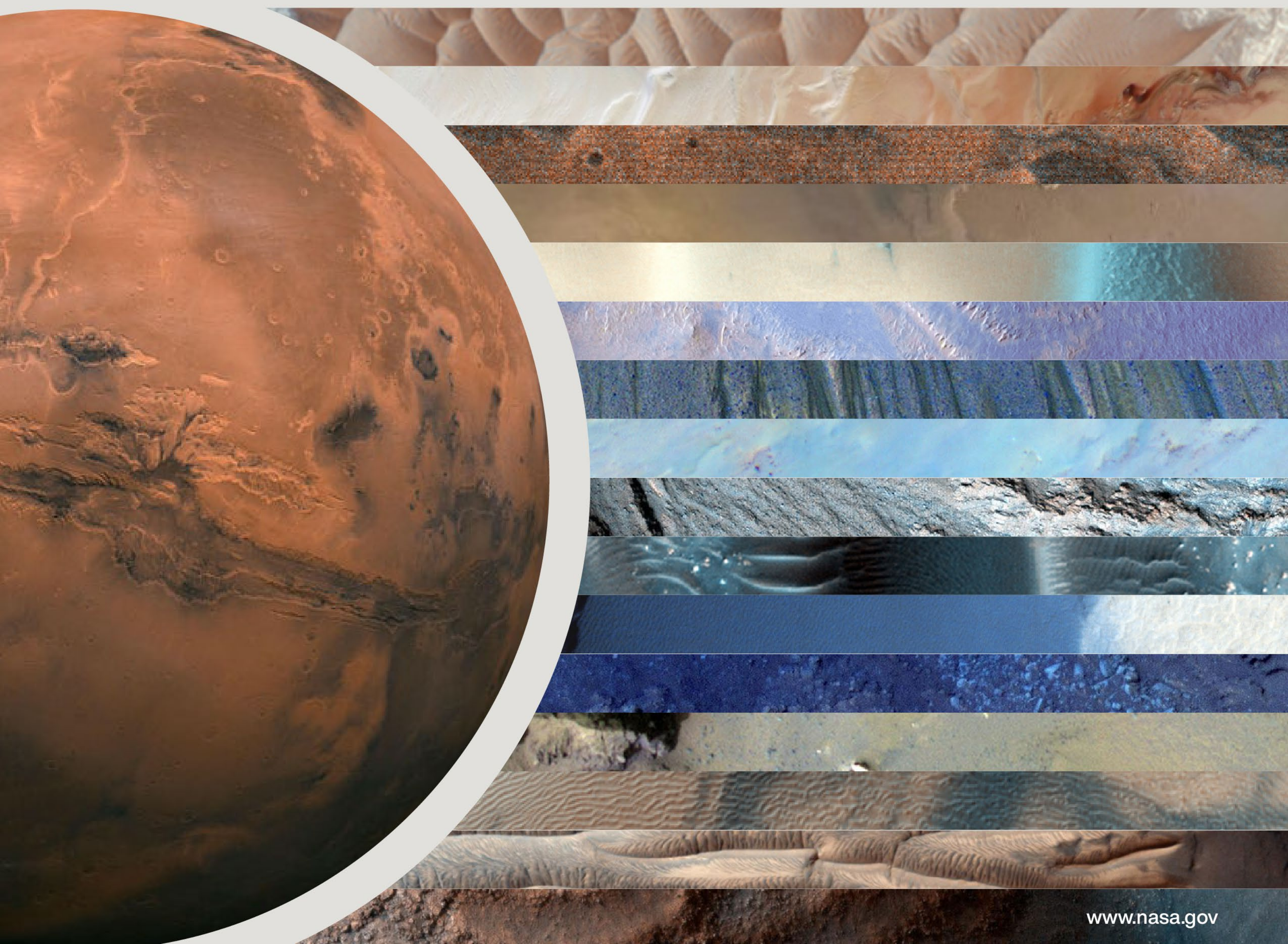

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Low-Cost Science Mission Concepts for Mars Exploration Final Report

This document is the final report of NASA's Low-Cost Science Mission Concepts for Mars Exploration Workshop, held March 29–31, 2022, in Pasadena, California.

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#LowCostMars2022 Website

https://www.hou.usra.edu/meetings/lowcostmars2022/

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1 Overview

Over the last 25 years, exploration of Mars has revolutionized our understanding of terrestrial planets and their evolution, addressing fundamental questions about the prevalence of life and the history of our solar system. The Red Planet serves as a unique natural laboratory because—unlike Venus, Mercury, and the Moon—it preserves an ancient record of how its surface and atmosphere interacted. Understanding geological and atmospheric processes, especially in the presence of liquid water, continues to shed light on key scientific questions regarding climate and habitability. However, numerous questions still remain, and in order to continue the pace of new discoveries from Mars, a shift in the paradigm of mission class and cost is likely needed.

To address a new approach to exploration at Mars, the Low-Cost Science Mission Concepts for Mars Exploration workshop, sponsored by NASA's Mars Exploration Program (MEP), was held on 29–31 March 2022 at the Westin Pasadena Hotel in Pasadena, CA. The conference website (#LowCostMars2022) gives complete program and presenter information.

Motivated by emerging small-spacecraft capabilities and innovative new mission concepts that offer opportunities for compelling science discoveries at Mars at unprecedented low costs, the workshop provided a forum for the Mars community—including scientists, engineers, technologists, and industry and NASA Center representatives—to share ideas and approaches for low-cost exploration of the Red Planet. In the context of the workshop, "low-cost" equates to mission costs that fall well below the current Discovery Program cost cap of ~$500M (Phases A–D). The recent Mars Architecture Strategy Working Group (MASWG) report suggested that small spacecraft missions in the $100–$300M cost range (including delivery) would provide the most achievable science per unit cost (Jakosky et al. 2020).

Specific topics for this workshop included

- Assessment of strategic Mars science questions well suited to investigation via low-cost, small-spacecraft missions
- Candidate low-cost mission concepts, relating science objectives to investigations, instruments, and spacecraft architecture
- Small-spacecraft capabilities for both orbital and landed Mars missions
- Innovative mission design approaches, including piggyback, rideshare, and new small-launch-vehicle capabilities for low-cost delivery of payloads to Mars
- New miniaturized instruments, avionics, and subsystems enabling highly capable small spacecraft
- Opportunities for international and commercial partnerships
- Emerging commercial NewSpace capabilities that can be leveraged for low-cost Mars exploration

With over 150 on-site participants and nearly 400 total registrants, including remote participants from 16 countries viewing the live stream, the meeting demonstrated the strong community interest in understanding the role that low-cost missions can serve as part of the future Mars Exploration Program.

The workshop was organized around five topical panels[1]. It included more than 70 invited and contributed talks and posters, with interactive poster sessions at the end of each of the first two days. *By the conclusion of the third day, a clear consensus emerged among workshop participants that low-cost missions in the $100M–$300M range (full life-cycle cost, including launch costs in 2022 dollars) not only could return compelling science results addressing fundamental Mars science questions, but were a critical next step for Mars exploration.*

Programmatically, a new, low-cost mission class would enable a higher cadence of missions, critical to addressing the wide range of outstanding fundamental Mars science questions. Earth science and Heliophysics have shown that missions in the sub-Discovery class are not only possible but can achieve compelling science results. Additionally, the past two decades have seen a steady increase in the capability—and cost—of Mars missions, culminating in the Mars Sample Return (MSR) campaign, which represents commitment to a major science objective in the delivery of samples to terrestrial laboratories but also to major funding over the rest of this decade. Without more

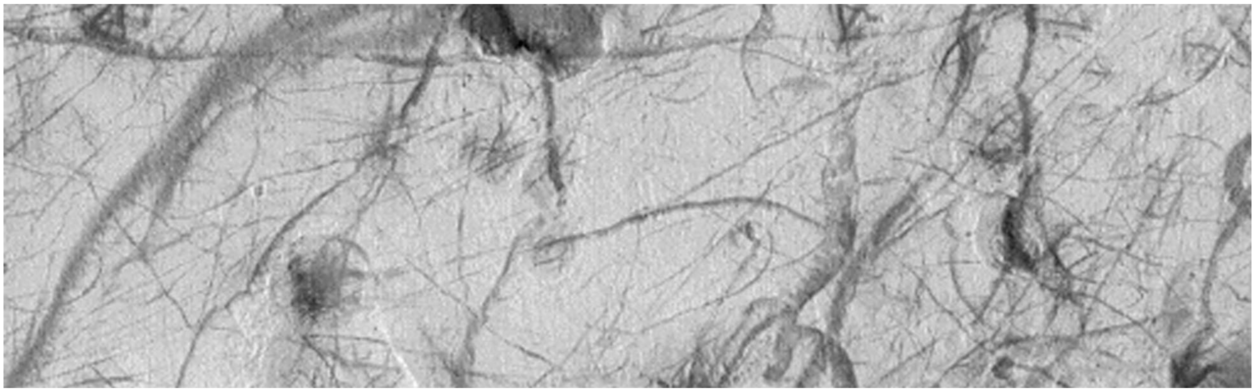
[1] 1) Mars Science Goals for Low-Cost Missions; 2) Lessons Learned in Low-Cost Mission Implementation; 3) Low-Cost Transportation to Mars; 4) NASA Technology Investments; 5) Commercial Innovation for Low-Cost Missions

diversity in the scientific return from Mars, many of the most fundamental questions about Earth's closest neighbor will go unanswered. The current NASA MEP Director, Dr. Eric Ianson, referenced this sentiment in his opening remarks at the workshop and described the program as being at an inflection point. He also observed that NASA's Earth Science Division has successfully integrated CubeSat, SmallSat, and hosted payload concepts to achieve significant reductions in mission cost while increasing science opportunities, an approach that MEP could leverage.

The results and discussion of this report are organized around seven general themes covered in the workshop:

1. Science achievable by low-cost missions to Mars (Section 2)
2. The challenge of getting to and communicating from Mars (Section 3)
3. The necessary technology developments to achieve low-cost missions (Section 4)
4. The role of commercial-academic-international partnerships (Section 5)
5. Risk considerations (Section 6)
6. Complementary studies and findings (Section 7)
7. Viable paths forward (Section 8)

Acknowledgements are in Section 9, References are in Section 10, and Acronyms are defined in Appendix A.



2 Science for Low-Cost Missions to Mars

Proof of Concept: Focused Science Questions

One of the most pressing questions for the MEP and planetary science is whether high-priority science could be accomplished with missions that would be considered "low-cost." This workshop answered that question with a resounding affirmative. Specifically, workshop participants presented a diverse and focused set of high-impact science missions and concepts. The Lessons Learned in Low-Cost Mission Implementation panel discussed the current development or execution of Mars missions consisting of ride-along payloads (e.g., the Mars Ingenuity Helicopter), rideshare-launched SmallSats or small-launch CubeSats (Mars Cube One [MarCO], Escape and Plasma Acceleration and Dynamics Explorers [EscaPADE]), and larger international satellites (e.g., the Emirates Mars Mission) with costs ranging from approximately $20M to $350M. The panelists also discussed current and future lunar missions (Lunar Polar Hydrogen Mapper [LunaH-Map], Lunar Trailblazer, commercial landers) at sub-Discovery cost caps, because much of the technology and instrumentation for lunar missions could be implemented in Mars missions as well. Presentations by multiple workshop participants also proposed credible approaches to doing Mars science with mature instrument and flight system technologies and mission implementations, many of which would have life-cycle costs of 25% to 50% of the present life-cycle costs of Discovery missions.

Science Addressable with Low-Cost Missions

A wide breadth of viable and focused science questions was proposed by workshop participants. There was overwhelming evidence that there would be many competitive proposals if there were an Announcement of Opportunity (AO) for a small-mission class. A subset of the missions described demonstrated readiness for near-term implementation, e.g., for 2026 or 2028 favorable launch windows, while others would require technology development to mature the relevant subsystems. *The diversity of the* *science motivations and the maturity level of the concepts clearly pointed towards the need for a consistent, high-cadence, low-cost mission class at Mars.*

Some of the most straightforward concepts included ongoing studies of space weather (effects of solar wind, flares, and storms) and meteorological observations (winds, clouds, dust, ices, temperature profiling), as well as high-resolution infrared imaging, all of which can be executed on orbital platforms with relatively low-mass and low-power instruments. Other candidates for low-cost missions with current technology and instrumentation included precision gravity measurements, wind measurements, and subsurface radar sounding.

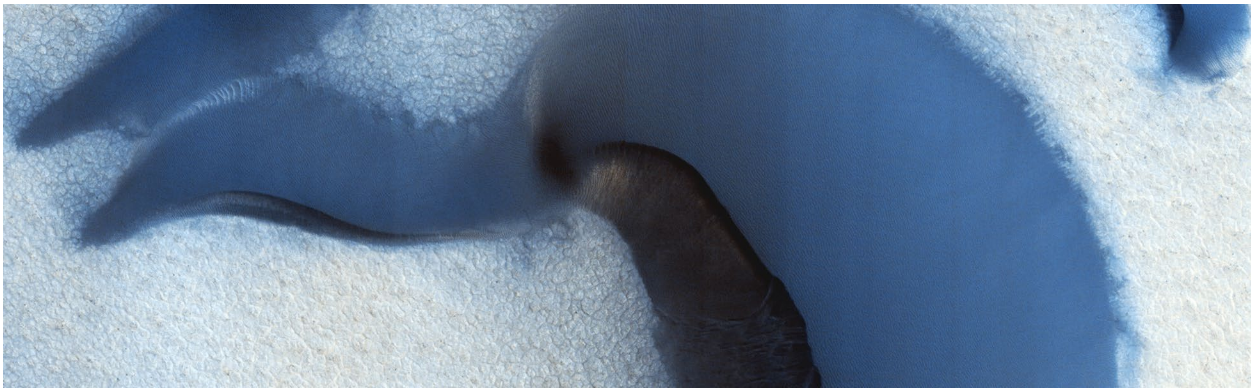
For access to the surface, a key technology challenge will be new, low-cost approaches, including high-g “rough” landers as well as lower-g “soft” landing approaches (see Technology Needs, Section 4), discussed at length in a recent Keck Institute for Space Studies (KISS) report, *Revolutionizing Access to the Mars Surface* (KISS 2022). Panelists discussed surface science investigations that included boundary-layer processes (winds, water-vapor exchange, trace gases), geophysics (remanent magnetism, seismology, electromagnetic sounding), and geology (polar, ancient habitats/geology). Participants also noted that Pathfinder-like or Mars Exploration Rover (MER)-like capabilities, with costs lowered by this heritage, could uniquely enable geological science investigations. These prospects could be further leveraged by Commercial Lunar Payload Services (CLPS) investments in low-cost mobility (rovers, hoppers), or via aerial approaches pioneered with Ingenuity and further matured with the planned Mars Sample Return fetch helicopters.

Table 1 highlights science questions that can be addressed at low costs and how they map to MEPAG and Planetary Decadal Survey goals.

It is important to note that, throughout the workshop, there was an understanding that some high-priority science and astrobiology questions at Mars fall outside the low-cost mission class and, at least for the present decade, are more appropriate for missions funded at higher levels. Missions that require complex analytical instrumentation or complex interactions (e.g., extensive sample manipulation) with Martian surface materials will likely remain in the purview of New Frontiers–class or Flagship-class missions. Missions with high-mass orbiting instruments or substantial data volume requirements are also challenging to execute at low cost.

Table 1. Low-cost Mars orbital, surface, and network science missions address MEPAG and Planetary Decadal Survey goals.

Low-Cost Science Traced to MEPAG Goals & Decadal Themes			MEPAG Goals Document				Origins, Worlds, and Life: Decadal Strategy for Planetary Science and Astrobiology				
	Science Mission Element	Example Techniques & Observables	I Life	II Climate	III Geology	IV Human	Q3 Origins	Q5 Interiors & Surfaces	Q6 Atmospheres	Q10 Habitability	Q11 Life
Orbital Science	Space Weather	Solar wind, flares, solar storms		X		X			X	X	
Orbital Science	Atmospheric Science	Winds, aerosols, temperature, dust		X		X			X	X	
Orbital Science	High-Resolution IR Imaging	Temperature, density			X	X		X			
Orbital Science	Geodesy	Crustal properties, seasonal processes		X	X		X	X			
Orbital Science	Subsurface Radar Sounding	Subsurface ice deposits	X	X	X	X		X	X		
Surface Science	Crustal Magnetism	Remanent magnetic fields			X		X	X		X	
Surface Science	Atmospheric Science	Winds, volatile exchange, trace gases, dust	X	X		X			X	X	X
Surface Science	Geophysics	Seismology, crustal properties, heat flow, subsurface water/ice			X	X	X	X			
Surface Science	Geology / Ancient Habitats	High-res imaging, chemistry, mineralogy, isotopes	X	X	X		X	X		X	X
Network Science	Seismology Network	–			X	X	X	X			
Network Science	Atm. Science Network	–		X		X			X	X	
Network Science	Orbital Network (e.g., ESCAPADE)	–		X		X			X	X	
		# Relevant Workshop Abstracts (63 total)	3	23	16	4					



3 The Challenge of Mars: Transportation and Telecommunications

The last decade has seen a tremendous growth in CubeSat and SmallSat capabilities. That growth has transformed the economy for small-spacecraft developments and has established a thriving marketplace of NewSpace suppliers introducing low-cost spacecraft components and innovative mission solutions. The CLPS approach to lunar landers has further fueled the expansion of low-cost planetary exploration systems. However, the bulk of these developments to date have been focused on Earth-orbiting and cislunar mission scenarios. Extending these approaches to Mars mission applications (and other planetary destinations) poses unique challenges that must be addressed to fully leverage emerging low-cost spacecraft capabilities at the Red Planet. In particular, the very large distance to Mars, relative to the Earth-Moon system, introduces demanding requirements in two key areas: transportation (getting the spacecraft to Mars) and telecommunications (getting the data back from Mars). Table 2 summarizes the challenges of transportation and telecommunications and approaches to mitigating them.

Transportation

Delivering a spacecraft to Mars demands much greater propulsive capability than delivery to Earth orbit or the Moon, with significant impact on mass, volume, and cost. However, a range of evolving capabilities promises to radically reduce the cost of delivering spacecraft to Mars. Options include piggyback rides with a Mars-bound primary mission, as well as launch to Earth orbit via commercial rideshare opportunities or dedicated launch on one of an emerging set of small, low-cost launch vehicles, combined with a propulsive stage to complete the transfer to Mars. Each mode has its advantages and disadvantages in terms of cost, flexibility of schedule and risk. NASA should serve as a clearing house for these opportunities, particularly for piggyback and rideshare opportunities on its own missions. A regular cadence of missions using various transports could energize commercial companies to develop and sustain such transport services.

There are a variety of launch vehicle options currently available and emerging, with competition spurring innovation and cost reduction. Small-launch-vehicle providers (e.g., Relativity Space, RocketLab, ABL Space, and Firefly Aerospace) could provide a flexible, high cadence of delivery of ~1000 kg to Earth orbit needed for a Mars mission, and its propulsive stage with many km/s of capability required to reach Mars destinations. There are caveats to this prospect; namely that small launch vehicles capable of >1000 kg to low Earth orbit (LEO) have yet to successfully launch, and projected small-launch-vehicle lift capability is currently limited to ~1000 kg, a limitation that can be highly constraining for chemical propulsion (CP) missions that have high propellant-mass fractions. Rideshare on larger reusable launch vehicles like the SpaceX F9 could also provide rideshare to destinations like geosynchronous transfer orbit (GTO) (or even lunar transfer orbits) at competitive pricing.

Technologies that could enable or enhance delivery from GTO:

- *Chemical propulsion systems with high ∆V capability* need to be developed to enable delivery to Mars science orbits (e.g., low Mars orbit, areostationary orbit) from GTO;
- *Chemical green monopropellant to provide 300–1,100 m/s propulsion* and support deep-space attitude and momentum management
- Robust technologies that can accommodate uncertainty on the launch vehicle (LV) side, such as *high-∆V modular propulsion stages or kick stages* capable of fitting within the constrained lift and volume envelopes of a small LV
- *High-throughput (>100 kg) solar electric propulsion (SEP) thrusters*, higher specific impulse (I_{sp}) and lower propellant-mass fraction for larger payloads within 1000 kg capability—minimizing transit time to Mars (<2.5 years) to minimize increased cost of mission operations with SEP compared to CP
- *Aerobraking and aerocapture technologies*, providing low-cost means of getting to low Mars orbit with greatly reduced propellant requirements

One intriguing concept discussed at the workshop is the notion of a propulsive “tug” that could carry multiple small spacecraft to Mars, delivering each to its final science orbit, thereby eliminating the need for each individual small spacecraft to implement its own large and costly propulsive system for Earth–Mars transfer and Mars orbit insertion.

Another aspect of the transportation challenge is finding low-cost approaches to getting to the Mars surface. Given the diversity of Mars environments, there is a need to explore many different locations, including those that are potentially habitable, to understand the history (i.e., the timing of events and major transitions) of a complex planet. Low-cost access to the Mars surface would also enable multiple surface missions to address science questions requiring networks (e.g., seismology) (see KISS [2022] for further discussion of surface missions).

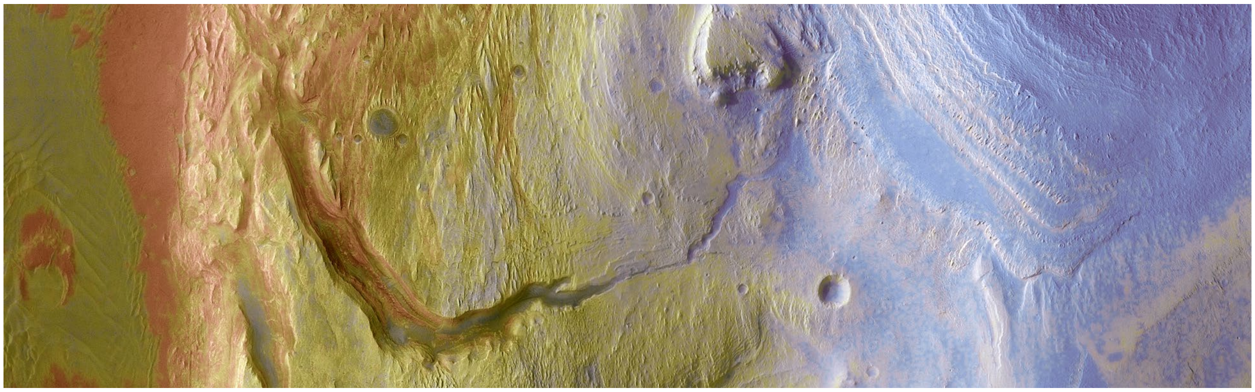
Telecommunications

Compared to telecommunications for small Earth-orbiting or lunar missions, telecom for small Mars missions can be extremely challenging, with Earth–Mars distances of up to ~2.5 AU, and with the small-spacecraft constraints of mass, volume, and power limiting the telecommunication subsystem's downlink capability. Compared to the emerging set of low-cost lunar missions, Mars represents a destination that is up to 1,000 times farther away. Because communication capability scales inversely with the square of distance, Mars represents a million-fold greater telecommunications challenge than the Moon. As a result, for Mars spacecraft, the telecom system can be a significant cost driver on overall mission costs. However, the Mars relay infrastructure can enable high data throughput while minimizing the size and cost of direct-to-Earth (DTE) SmallSat hardware, in some cases (e.g., for piggyback to Mars) completely eliminating the need for a DTE telecom system.

Today's Mars relay network, comprising Mars science orbiters with added relay capabilities (e.g., the MRO and MAVEN satellites), has greatly enhanced the data return from inevitably power-constrained surface landers and rovers. However, this relay infrastructure is aging and will need to be augmented within the coming decade. This would seem an ideal opportunity for NASA to engage commercial companies to provide a *next-generation relay service* with increased contact time, higher data rates, and support not just for surface spacecraft but for orbiters as well. Such a relay capability could enable even CubeSat-class small orbiters to return MRO-class data volumes and would be enabling for high-data-throughput missions incorporating high-resolution imagery, spectroscopy, and/or SAR mapping instruments. Such a relay service would also serve as a stepping-stone towards enhanced relay capabilities that will ultimately be needed by human Mars explorers. Key technology needs for such a next-generation relay network include *high–effective isotropic radiated power (EIRP) Ka-band DTE links* for the relay orbiters; *energy-efficient proximity links* supporting high-rate forward and return relay services to user spacecraft; *algorithms to extract position, navigation, and timing (PNT)* information from radio metric tracking on the proximity links; and interoperable standards like *delay-tolerant networking* to support seamless, highly automated network protocols.

Table 2: Workshop participants identified mitigations for the two most pressing challenges of Low-cost Mars missions—transportation and telecommunications.

Challenge (Relative to Earth-Orbiting & Cislunar Missions)	**Mitigation**
Transportation: High propulsive cost to reach Mars	• Rideshare launch opportunities
	• New small-launch-vehicle options
	• High-ΔV kick stages for transfer from GTO to Mars
	• Aerobraking and aerocapture technologies
	• Space tug to deliver small spacecraft to Mars destination orbits/trajectories
Telecommunication: 1000-fold greater distance to Mars than to the Moon	• Next-gen Mars relay orbiters supporting both landers and orbiters
	• High-EIRP Ka-band DTE links
	• Energy-efficient proximity relay links
	• Position/navigation/timing services derived from relay links
	• Delay-tolerant network protocols for seamless data transfer over interplanetary distances



4 Technology Needs

In addition to the challenges of transportation and telecommunication, a variety of other key technologies and services were identified to enable and enhance low-cost missions to Mars (Table 3). The list in this section is not exclusive but serves to highlight areas for technology development that are attainable in the near-future.

Table 3: Low-cost Mars missions require—and inspire—new technology developments attainable in the near future.

Area	Technology
Science Instruments	• Instrument miniaturization and ruggedization
Entry, Descent, and Landing	• Low-cost minimum-complexity "rough" lander • Reduced-cost small propulsive lander for "soft" delivery of small payloads
COTS Architecture and Reliability	• Rapid characterization and infusion of COTS components • Avionics architecture to achieve required system reliability
Surface Mobility and Manipulation	• Low-cost options for surface mobility (rovers, hoppers) • Low-cost techniques for shallow subsurface sampling and handling
Aerial Mobility Platforms	• Next-generation rotorcraft with increased payload capability and traverse range
High-Performance Computing and Autonomy	• Greatly increased onboard processor capability • AI/ML algorithms leveraging increased computational capability to enable highly autonomous operations

***Instruments*.** Highly sensitive and capable *miniaturized instruments* are a key to enabling small, low-cost missions to Mars. Presently, low-cost orbiter and lander missions are highly constrained for mass, volume, power, and data; miniaturization of instruments is critical to fit within current payload mass capability. Instrument ruggedization to tolerate extreme Martian environments like rough-landing or polar-landing sites could also enable new types of low-cost surface missions.

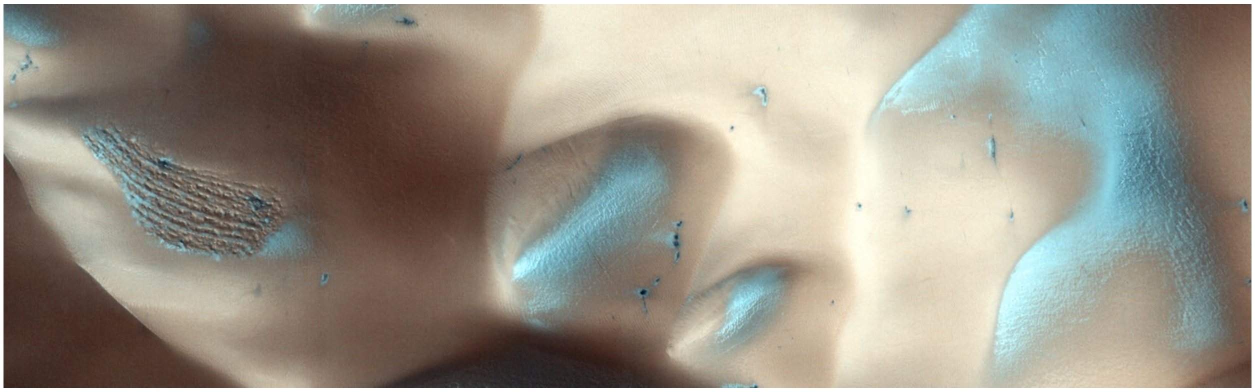
***Entry, Descent, and Landing (EDL)*.** The diversity of Mars environments calls for frequent access to the surface, driving a need for development of *low-cost lander technology*. A low-cost surface-delivery system could also enable surface network science. Rough landers, which dispense with parachutes and retropropulsion systems, using simple ballistic entry and impact absorption to control landing loads to <2000 g upon landing, could deliver small, 10–20 kg payloads to the surface at a very low cost (<$100M); however, these rough landers will require instrument ruggedization and packaging augmentation to survive their higher g-loads. Low-cost soft landers, with smart EDL systems for robust propulsive descent, can provide lower landing loads but probably at higher costs.

***Commercial off-the-Shelf (COTS) Architecture and Reliability*.** Infusion of *COTS components* offers opportunities for high-performance, low-cost, low–size, weight, power (SWaP) solutions (e.g., the Qualcomm Snapdragon processor on the Ingenuity helicopter). However, COTS solutions will demand careful testing as well as appropriate architectural design to achieve required levels of system reliability in Mars environments. Standardization of spacecraft and instrument accommodation will require more than a "one-size-fits-all" approach and more likely will be based on a *common avionics architecture* that can infuse COTS components into spacecraft avionics within a Class D or tech demo risk posture.

***Surface Mobility and Manipulation*.** Small, low-cost *mobile platforms (rovers or hoppers)* will enable science access to diverse geologic targets. Access to the subsurface has the potential to open new windows to understanding the geochemical and astrobiological history of the planet. While deep drilling is likely outside the scope of low-cost missions, there is interest in low-cost methods for *shallow subsurface sampling* and a need for *sample-handling and -manipulation techniques* that are compatible with low-cost missions.

***Aerial Mobility Platforms*.** Aerial platforms allow for transformative science on Earth (e.g., geologic mapping, atmospheric science, magnetometry) that can be translated to Mars. Workshop participants saw promise in further technology development of an *array of aerial vehicles*, particularly next-generation rotorcraft that build on the success of the Ingenuity helicopter, and that could deliver meaningful payloads to challenging terrains. Such aerial vehicles could leverage low-cost methods of getting to the surface (e.g., mid-air deployment) with mobility that would enable a range of innovative mission concepts.

***High-Performance Computing (HPC) and Autonomy*.** *High-performance computing* technology would enhance both orbiter and lander systems. HPC can be used to implement software-defined radio capabilities, providing dual functionality of command and data handling and telecom subsystems. Autonomy will also support reductions in operations costs, allowing smaller ground teams to manage spacecraft operations while reducing ground-in-the-loop time. New applications of *artificial intelligence and machine-learning algorithms* can leverage increased flight-processor performance for greater autonomous capabilities, including change detection, hazard avoidance, and many other functions.



5 International, Academic, and Commercial Partnerships

During the workshop, multiple panels examined the potential for partnerships to reduce the total cost for mission execution and optimize collaboration across organizations. Before presenting a synthesis of the discussion, it is important to note that partnerships can exist in different forms. There can be coordination, collaboration, and interdependence, as previously discussed in the MASWG report (Jakosky et al. 2020):

- Coordination can be represented by multiple agencies or entities conducting missions or research in parallel, increasing the scientific return but not directly affecting cost. Coordinated observing campaigns of the same region of Mars's surface or atmosphere are common examples.
- Collaboration can be in the form of a partner providing an instrument or augmented science-enhancing spacecraft subsystem to add science and reduce cost to NASA.
- Interdependence involves a partner providing a critical element, such as LV, rideshare, or a component of a mission or program, upon which other elements depend to substantially reduce cost to NASA.

International Partnerships

NASA has a strong record of international partnering in Mars exploration, including contributed science instruments from partner agencies on NASA missions (and NASA-funded instruments on international partner missions), a NASA-contributed relay payload on ESA's ExoMars Trace Gas Orbiter, and the current NASA-ESA partnership on the Mars Sample Return campaign. Opportunities here will grow significantly as emerging space-faring nations express interest in Mars exploration.

While the ongoing pandemic inhibited most international travel to the Low-Cost Science Mission Concepts for Mars Exploration workshop, there were online participants from sixteen countries. Speakers advocated ongoing international collaboration and outlined opportunities for partnerships with varying degrees of interdependence of the elements. There was clear consensus at the workshop that there is tremendous value in fostering collaborations among the many governments and entities interested in Mars exploration. For example, the international landscape of missions to Mars has changed substantially in the last 10 years, with the space agencies of India, China, and the United Arab Emirates—in addition to NASA and ESA—all presently operating missions at Mars. JAXA has also planned missions to the Mars system beginning in 2024. Speakers also noted that while the cost of an entire Mars mission is beyond the budget of many agencies, contributions of science instruments or subsystem hardware are within the capabilities, reach, and interests of an increasing number of space-faring nations. The International Mars Ice Mapper (I-MIM) is a mission concept for subsurface sounding to measure near-surface properties and ground ice. I-MIM motivated by climate science and human exploration (I-MAP MPS 2022) and is an example of a mission concept in which partners would share substantial interdependence, thereby allowing the cost for each participating agency to fall into the low-cost mission category[2].

When NASA engages in international collaboration, it is necessary that (1) the relevant scientific communities are involved in the definition and execution of joint missions; (2) to the extent possible, missions and instruments are competed openly to maximize science return; (3) NASA-supported mission participants on non-NASA missions (instrument and science team members, participating scientists, interdisciplinary scientists) are supported financially at adequate and appropriate levels to achieve the mission objectives; and (4) a regular, predictable cadence of NASA mission opportunities is established so that other agencies can align their budgets and programmatic planning for contributions or missions with significant interdependence.

Academic Partnerships

Several examples from the Lessons Learned panel described the immense benefit of academic partnerships for low-cost space missions. In many instances, the hardware provider or the mission operations center was an academic institution (e.g., University of California, Berkeley/Space Science Lab, Arizona State University/Interplanetary Laboratory, University of Arizona/Lunar and Planetary Laboratory, University of Colorado/Laboratory of Atmospheric and Space Physics [LASP], California Institute of Technology, University of Michigan/Space Physics Research Laboratory). Participants from these institutions emphasized common themes that have allowed them to design and deliver missions at low cost:

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[2] I-MIM was descoped in the NASA FY23 budget concurrent with the execution of the Low-Cost Mars workshop.

- Focused science objectives where a science concentration could build on the knowledge of larger, earlier missions
- Small teams that emphasize engineers working across disciplines
- Fewer instruments, reducing complex commissioning and operations
- Use of commercial parts where feasible and available
- Student staffing of select roles

In addition to cost savings from academic partnerships, speakers pointed out that these partnerships advance the nation's science, technology, engineering, and math (STEM) goals by broadening and diversifying student participation in STEM fields. Providing opportunities to work on Mars missions as part of their training may serve to recruit and retain more university students in STEM.

It should also be noted that streamlining NASA requirements (Class-D tailoring of 7120.5F requirements) and contracting simplification or use of grant mechanisms were cited as important factors for keeping within cost and schedule and enabling commercial and academic entities to lead mission implementation.

Commercial Partnerships

The explosive growth of commercial space activities, with many NewSpace firms entering the market, offers significant new opportunities for commercial partnering. Consequently, this is the dimension of partnership that is evolving most rapidly and that might offer the biggest impact on driving down the cost of future Mars missions through innovation and competition. Industry has always played a significant role in NASA's Mars exploration, via system contracting for missions like MRO and Interior Exploration Using Seismic Investigations, Geodesy, and Heat Transport (InSight), and via major subsystem deliverables for in-house missions like MER, Mars Science Laboratory (MSL), and Mars 2020. However, NASA is more recently exploring new modes of partnering with industry via service-based paradigms such as the the Commercial Crew and Cargo Program and the CLPS program. These service-based models leverage demonstrated industry capabilities, with the commercial provider taking greater responsibility for development and operations of flight systems, using their own processes and practices to achieve significant cost savings.

Two panels explored various aspects of these commercial opportunities. The "Low-Cost Transportation to Mars" panel examined three methods to significantly reduce the cost of getting to Mars, particularly applicable to small spacecraft: (1) piggyback on a Mars-bound primary spacecraft (relatively infrequent at present); (2) Earth rideshare (which requires propulsion for the Mars spacecraft after separation); and (3) dedicated launch, including the emergence of new small- to medium-class launch vehicles. Reusability of launch vehicle elements has led to significant reduction in launch costs. Another promising development is NASA's new Venture-Class Acquisition of Dedicated and Rideshare (VADR) Launch Services program, which aims to achieve reduced costs for launch services for Class D (or higher-risk-category) missions through streamlined NASA oversight, a lower level of mission assurance, and increased use of commercial practices relative to traditional NASA Launch Services (NLS) contracts. There was a consistent call for investing in technologies or developing approaches for bracketing delta-V requirements that can accommodate uncertainty on the launch vehicle side.

Small launch vehicles are not the only area of commercial growth that might benefit low-cost Mars missions. SpaceX reported that their Starship would be ready later this decade to deliver very large payloads to Mars at greatly reduced cost per kilogram, offering an alternative strategy to focusing strictly on small spacecraft miniaturization and instead leveraging higher-SWaP, but lower-cost, spacecraft and payload implementations.

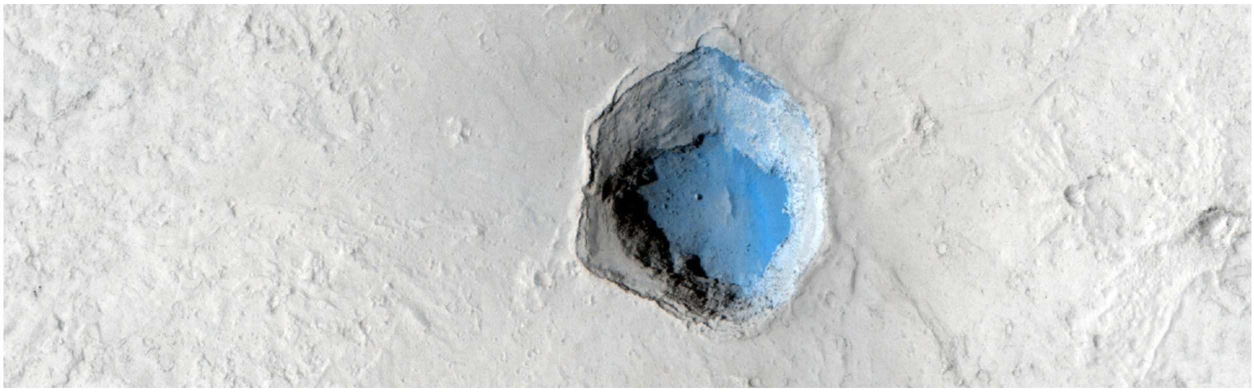
Another important component of commercial partnerships that the panelists noted was the necessity of regular flight cadence at each launch window to lower cost by amortizing risk and expense over an entire program.

A second panel, "Commercial Innovation for Low-Cost Missions," highlighted both the possibilities and the challenges associated with achieving significant cost reduction for future Mars missions. Increased use of commercial parts offers a pathway to increased performance with greatly reduced SWaP, but ensuring long life consistent with planetary mission timelines will demand thorough design and testing. The notion of a "standard Mars spacecraft bus" was raised, but, significantly, multiple panelists felt that this approach was too restrictive. Instead, they recommended a modular spacecraft architecture and low-cost spacecraft components that could be quickly tailored to a given mission's instrument suite and science operations concept.

There was consensus that NASA should assess whether the CLPS paradigm could be adapted for Mars. While acknowledging that NASA might likely be the only customer in the near-term, the panelists echoed a finding from the MASWG study: "A successful Mars-focused Commercial Mars Payload Services ('CoMPS') could serve as a programmatic vehicle to allow, at reduced cost, development of technologies for future exploration as well as delivery of specific science payloads" (Jakosky et al. 2020). This program would have the added benefit of expanding the market for services and capabilities that NASA invested in developing at the Moon for use in lowering costs to Mars and other planetary bodies. As noted in the *Revolutionizing Access to the Mars Surface* report (KISS 2022), a services model redistributes the risk from solely NASA to multiple institutions and might permit bolder risk postures, which can potentially realize cost savings for NASA while fostering innovative approaches.

In addition to commercial payload delivery, several other potential opportunities for commercial services were discussed over the course of the workshop:

- A commercially built and operated constellation of orbiters could provide next-generation Mars relay telecommunication and navigation services to NASA (and other) customer missions on a fee-for-service basis. Such capabilities would be enabling for future low-cost missions by relieving the user spacecraft of having to handle the long-haul communication with Earth. Such a constellation could leverage large investments in Earth-orbiting and—in the coming years—lunar telecommunication networks.
- Propulsive “tugs” could deliver small spacecraft directly to their Mars science orbits. A tug launched in each Mars launch opportunity could carry multiple small spacecraft—potentially from multiple space agencies—sharing transportation costs and greatly simplifying the design of the individual customer small spacecraft.
- Future high-resolution Mars orbital imaging could be provided on a fee-for-service basis, similar to terrestrial imaging service providers such as Planet, Maxar, and BlackSky.



6 Risk for Low-Cost Missions

Throughout the workshop, a number of perspectives on risk assessment entered the dialogue, for the risk tolerance of NASA missions differs for each mission class and within each Science Mission Directorate (SMD) Division, but all have to be accepted by NASA's customers: the Office of Management and Budget (OMB), Congress, the Government Accountability Office (GAO), and the public at large. Lowering mission cost suggests that more missions could be flown and that loss of any one mission would soon be recovered by another, much like the commercial approach for rapid development for space technology, which lives with spacecraft failures. However, a failure (or successive failures) might be enough to jeopardize a program of even low-cost missions. The loss of the Mars missions Mars Climate Orbiter and Mars Polar Lander in 1999 resulted in a complete restructuring of NASA's Mars Program to reintroduce the necessary systems engineering for mission success. Thus, a balance of risk, mission development cycle, and technology and science return must be assessed for a new low-cost mission class (Figure 1).

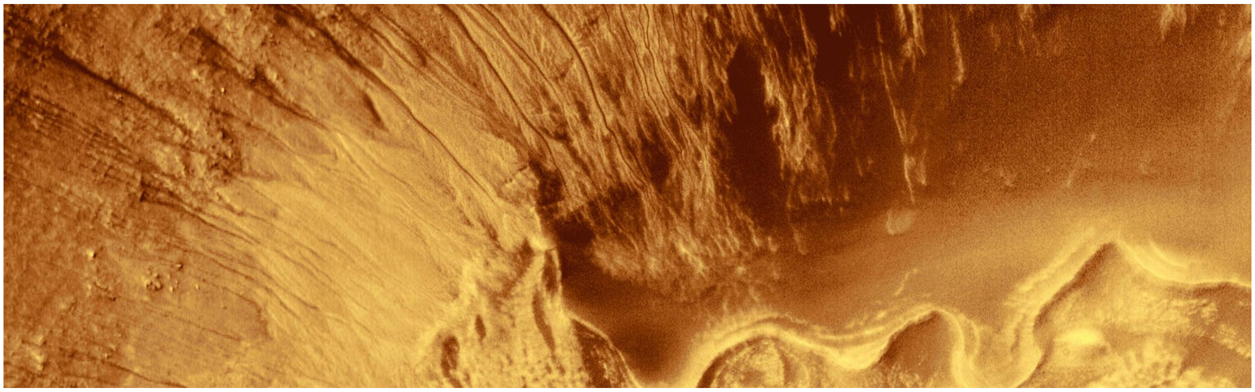
The old paradigm of doing more at lower cost was often predicated on the notion that lower cost would inherently be more risky: A lower budget resulted in the inability to pay for the extensive design/review, test/review, and system test/review cycles required for one-of-a-kind developments. Efforts to develop standardized spacecraft buses have encountered obstacles in the past on cost to either accommodate all possible payloads or to

Figure 1. A program of low-cost missions can balance cost, risk, and schedule pressures and achieve compelling science by taking advantage of a robust commercial space economy to standardize at the subsystem and parts levels.

restrict the payload/operational capabilities to the point where compelling science is not achievable.

However, a new paradigm appears possible for a program of low-cost missions that standardizes at the subsystem and parts levels and uses qualified "catalog" capabilities of a robust commercial space economy to build in the flexibility needed to address science and exploration objectives. While there will still be a need for one-of-a-kind developments, a program of low-cost missions provides exactly the kind of approach that could demonstrate a balance of both standardized and mission-unique developments while still accomplishing excellent science. Even at the current juncture, choices about redundancy and fault-protection approaches are being carefully tailored for commercial and NASA lunar programs. As discussed in Section 5 of this report, focused science combined with small engineering teams building only a few instruments can produce compelling science at very low cost.

The goal of a low-cost missions to Mars program is to achieve high chances of success for tailored missions without undertaking extensive and expensive documentation, development, and testing that will not materially affect mission success. This could include bulk buys or lists of certified suppliers of particular parts, simplified fault-protection approaches and testing requirements (at the system rather than parts level), streamlining documentation and reporting while maintaining the level of communication necessary. This approach aims for mission success but does not try to account for the unlikely corner cases that could cause mission failure—cases that often add a much higher percentage of cost than their ability to lower risk (e.g., ATLO costs increase by 30% while risk is only lowered by 2–4%). This approach requires some more experienced team members as well as careful and reasonable expectations for mission requirements. NASA could strongly leverage commercial partners to apply their best practices rather than imposing extensive NASA processes on risk assessment for low-cost missions. Service-based procurement paradigms could allow for this measure, resulting in reduced cost at acceptable risk that is assumed by the commercial provider as well as by NASA. Nevertheless, the requirements with respect to cost cap and schedule must be crafted so that they do not force low-cost missions to make poor choices.



7 Complementary Findings

A new mission class within NASA's MEP would require augmented or redirected funding, which naturally would give rise to the question, "Why Mars?" A number of reports have studied and addressed the subjects of Mars exploration, planetary exploration, and low-cost mission approaches, with findings complementary to those of this report.

Mars Architecture Strategy Working Group (MASWG) Report (2020)

Scientifically, the "Why Mars?" question is aptly captured by the MASWG report (Jakosky et al. 2020), which synthesized the return on the taxpayer investment that Mars exploration offers:

- Outstanding access to environments fundamental to the search for past and/or present signs of life;
- An unparalleled opportunity to study climate and habitability as an evolving, system-level phenomenon, with Mars and Earth apparently having passed through similar stages as they evolved to their present states;
- The best place in the solar system to study the first billion years of the evolution of a habitable terrestrial planet;
- Outstanding opportunities to inform our understanding of the evolution of exoplanets by investigating its climate, prebiotic, and possible biological history; and
- A compelling destination for human exploration and science exploration synergism. (p. 2)

The MASWG report's Findings 5 through 9 also align strongly with those of this report:

Finding 5: Utilize all mission size classes.

- A Mars program can most effectively address the full range of key science objectives by appropriately utilizing missions in all size classes, in addition to MSR. The key is to match the mission class to the science objective. . . .

Finding 6: Small-spacecraft technology.

- Rapidly evolving small-spacecraft technologies could enable measurements that address many key science objectives at Mars. This class of missions could become an important component of robotic exploration of Mars by enabling a higher cadence of scientific discovery at affordable cost. . . .

Finding 7: Affordable access to the surface.

- A critical scientific need for Mars exploration is affordable access to multiple places on the Martian surface with adequate payload/ mobility to make the measurements that would revolutionize our understanding of the Mars system. . . .

Finding 8: Commercial activities and potential partnerships.

- Purely commercial or commercial–government partnerships for exploring or supporting the exploration of Mars, where the private entity bears a reasonable fraction of the investment risk, do not yet exist. A successful Mars-focused, CLPS-like program might serve as a programmatic vehicle to allow—at reduced cost but perhaps increased risk—development of technologies for future exploration as well as delivery of science payloads. . . .

Finding 9: International collaboration.

- There is tremendous value in developing collaborations between the many different governments and entities interested in Mars exploration. (pp. 26–29)

Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023–2032 (2022)

The Low-Cost Science Mission Concepts for Mars Exploration workshop took place in March of 2022, before the April 19, 2022, release of the Planetary Decadal Survey (National Academies 2022), and the findings of this workshop are independent from those of the Decadal Survey. However, the findings of the workshop are complementary to those in the Decadal Survey, which states the following:

- "There remain many fundamental science questions at Mars beyond those addressed by MSR" (p. 603).

- "Thanks to Mars's relative accessibility, international partners eager to pursue partnerships with NASA, and increasing capabilities of small spacecraft, effective coordination by MEP this decade can support a mission cadence to enable ongoing discovery along multiple arcs of priority science goals (see MASWG report [Jakosky et al. 2020])" (p. 603).
- "New, rapid, and low-cost exploration techniques using proven technology advancements, such as innovative landing methods, small satellites, and aerial vehicles, can be part of the MEP strategy to advance scientific and human exploration goals" (p. 603).
- "Recommendation: NASA should maintain the Mars Exploration Program, managed within the PSD, 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" (p. 603)
- "NASA should evaluate the future prospects for commercial delivery systems within other mission programs and consider extending approaches and lessons learned from CLPS to other destinations, e.g., Mars and asteroids" (p. 605).

KISS Workshop (2021): Revolutionizing Access to the Martian Surface

In addition to the MASWG and Planetary Decadal studies, a KISS workshop held in 2021 was aimed at increasing access to the Martian surface. Central to the strategy coming out of the KISS workshop is "completing more Mars activities at significantly lower per-unit cost than traditional NASA Mars missions" (KISS 2022, Section 4), an observation closely aligned with the findings of this report. The three main elements of the KISS strategy can be summarized as shown below:

1. *Frequent: Two Missions at Every Opportunity*

   A program of Mars exploration that is based on frequent missions can reap benefits that are self-reinforcing and increase the efficiency and efficacy of the effort, achieving multiple science objectives, sending market signals that enable development of components shared across missions (reducing nonrecurring engineering), and allowing single missions to be more risk-tolerant because risk is spread programmatically over multiple missions.

2. *Affordable: Mostly Low-Cost; Occasional Larger Missions*

   While the large flagship-level missions play a critical role in advancing our understanding of Mars and its long history, the low-cost and mid-range missions also have made crucial contributions. Frequency requires affordability, and affordability is realized by processes that generate components and subsystems with enough frequency to reduce nonrecurring engineering.

3. *Bold: Accepting Risk Appropriate to Lower Cost; Shared Responsibility for Risk*

   If risk is spread programmatically across multiple missions and partner institutions, encouraging all parties to be tolerant of carefully considered risk for each mission can lead to better science, more engaging missions, and more innovative solutions. Both mission designers and principal investigators have the opportunity to make choices that take advantage of the opportunity to repeat missions, correct mistakes, and learn from failures if there are multiple, frequent opportunities.

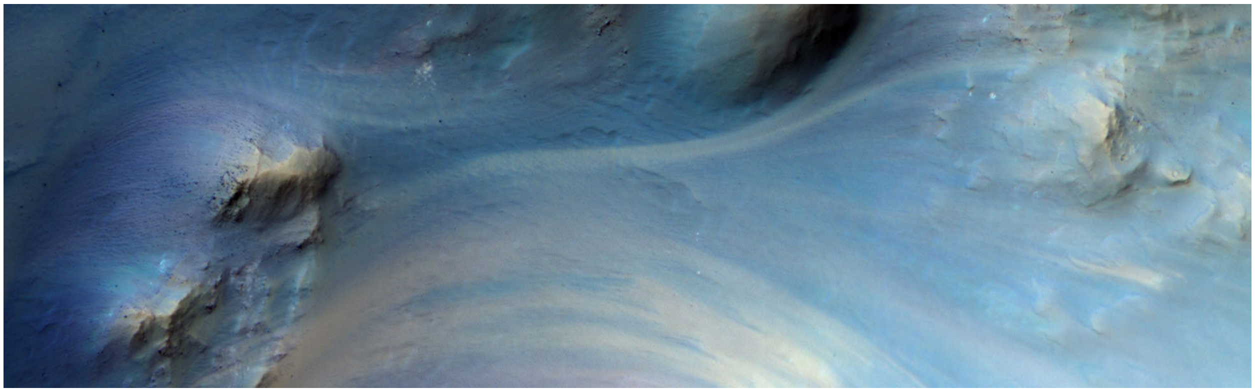
NASA Access 2 Space Workshop: Summary Report(2020)

The NASA Access 2 Space workshop, held at the Johns Hopkins University Applied Physics Laboratory (APL) in 2020, solicited community input on the creation and management of an ESPA Class-2 payload pipeline for NASA SMD launches. The Access 2 Space final report (Tan 2020) clearly outlined the need for technology developments in line with lower-cost missions:

- *Finding 1:* A pipeline of ESPA-class spacecraft will enable new system science and sensor development, but significant upfront planning is needed to ensure these missions are compatible with primary mission launch parameters and environments.
- *Finding 2:* Development of a multi-spacecraft ESPA-class payload pipeline enables sustainable long duration continuity observations.
- *Finding 3:* ESPA-class instrument development fills a capability gap between CubeSat and flagship missions for novel science observations. . . . (p. 3)
- *Finding 7:* ESPA-class payloads that are identified early and minimize complexity increase the manifest options towards a variety of launch vehicles, while lowering the risk to the primary mission.
- *Finding 8:* Dedicated launch services and other ESPA-class launch/deployment options can further enable ESPA-class payload pipeline development via multiple alternative access-to-space approaches.
- *Finding 9:* Development of an ESPA-class payload rideshare rating system upon mission selection could streamline matchmaking of payload pipelines to launch opportunities. . . . (p. 4)
- *Finding 12:* Small satellite subsystem technologies have rapidly matured, improving performance and reliability, but focused investments and strategic

partnerships are needed to advance such technologies for deep space ESPA-class systems. . . . (p. 5)

- *Finding 16:* Standardization of services and solicitation of concept studies for launch opportunities directly enhance ESPA-class payload pipeline development.
- *Finding 17:* Overall mission oversight-related activities amongst the primary and ESPA-class rideshare payloads should align with the lifecycle of the primary mission when practical.
- *Finding 18:* Lack of funding continuity and training opportunities present challenges for small university investigators where strong institutional support is needed for new and/or early career PIs to impact the diversity of payload pipeline development for ESPA-class missions. (p. 7)



8 Viable Paths Forward

The Low-Cost Science Mission Concepts for Mars Exploration workshop confirmed that compelling science can be achieved through a new mission class in the sub-Discovery range. Based on the range of mission concepts presented, missions in the $100M–$300M range (FY22 dollars or 20–60% of Discovery Phase A–D costs) can address key science questions at Mars, consistent with the MASWG report. In closing, we summarize here some of the key strategies and potential next steps that were identified over the course of the workshop to realize this vision of a new low-cost mission class becoming a core element of the future Mars Exploration Program.

- *Formulating focused science questions*:
    - In order to keep costs below Discovery-class, focused science questions (along the lines of those selected under Small, Innovative Missions for Planetary Exploration [SIMPLEx]) are necessary. With focused questions, often engineering models or highly matured instruments can be applied. Additionally, fewer and less complex instruments can fulfill the science requirements and simplify requirements on mission systems.
- *Conducting mission concept studies*:
    - The Planetary Science Division has offered opportunities such as the recent Planetary Mission Concept Studies and the Planetary Science Deep Space SmallSat Studies (PSDS3) that have enabled maturation of science mission concepts. A similar set of studies funded by MEP and focused on low-cost mission concepts would provide an opportunity to refine traceability to focused Mars science questions, establish viable implementation approaches, identify key technology needs, and better quantify mission cost, laying the groundwork for strong community response to a potential future low-cost Mars mission AO.

- *Investing in enabling technologies*:
    - A well-funded, competed technology program aimed at identifying and closing capability gaps for low-cost Mars missions (relevant also to other destinations) will be key to enabling this new mission class. Such a program should aim to draw on the best ideas from across NASA, academia, and industry.
- *Establishing commercial, international, and academic partnerships*:
    - Commercial partnerships will be critical for the low-cost mission class, whether at Mars or any other planetary body. NASA's aim should be to leverage emerging commercial capabilities in a cost-effective manner; this should include consideration of service-based procurement mechanisms with reduced NASA oversight in areas where industry has demonstrated capability.
    - International partnerships offer opportunities for cost-sharing to make larger endeavors low-cost to NASA and can provide a path to Mars for emerging space-faring nations.
    - Academic partnerships have demonstrated cost-effective approaches to mission implementation and operation while also providing hands-on educational opportunities that enhance the nation's future STEM workforce.
- *Balancing risk and mission cost*:
    - A subset of experienced team members and careful, reasonable expectations for mission requirements will be critical to accepting a higher risk-tolerance while delivering successful missions.
    - NASA could strongly leverage commercial partners to apply their own best practices rather than imposing NASA processes on milestone-tracking and risk-assessment for low-cost missions.
- *Achieving a high mission cadence*:
    - Having a regular cadence of Mars mission opportunities (ideally one to two missions every 26 months) was cited throughout the workshop as an essential objective, key to realizing an increased breadth of Mars science return while reducing individual mission costs.
    - Increased mission cadence also provides an environment where a program-level approach toward individual mission risk can be developed. With lower mission costs and frequent flight opportunities, some per-mission risk can be accepted, creating a positive feedback loop of further cost reductions and increased mission cadence, aimed at maximizing overall program science return.

- *Establishing infrastructure for low-cost Mars missions*:
  - Next-generation Mars relay orbiters, replenishing our current capabilities for energy-efficient support to Mars surface assets, but also for the first time providing high-bandwidth relay services to small Mars orbiters, will be essential for future low-cost Mars missions.
  - A standardized Mars tug delivery capability, procured as a service from industry, could enable placement of simple, low-cost spacecraft directly into their final science orbits or entry trajectories, simplifying and reducing the cost of delivering individual small spacecraft.

In conclusion, low-cost missions are poised to become a central element of a robust future Mars Exploration Program. And as several participants stated, "the next big thing just might be a small thing!"

9 Acknowledgements

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Pre-Decisional Information—for Planning and Discussion Purposes Only.

Banner Image Credits

Section 1: Perseverance Looks toward “Santa Cruz”: https://mars.nasa.gov/resources/26616/perseverance-looks-toward-santa-cruz/

Section 2: Martian Dust Devil Tracks: https://mars.nasa.gov/resources/5299/martian-dust-devil-tracks/

Section 3: Sand Dunes Near the North Pole: https://mars.nasa.gov/resources/5249/sand-dunes-near-the-north-pole/

Section 4: Gale Crater's History Book: https://mars.nasa.gov/resources/5253/gale-craters-history-book/

Section 5: Frost-Covered Dunes in a Crater: https://mars.nasa.gov/resources/5254/frost-covered-dunes-in-a-crater/

Section 6: Small Floral-Shaped Volcano: https://mars.nasa.gov/resources/5250/small-floral-shaped-volcano/

Section 7: Gullies on Mars: https://mars.nasa.gov/resources/5303/gullies-on-mars/

Section 8: Colorful Streaks: https://mars.nasa.gov/resources/5252/colorful-streaks/

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Appendix A: Acronyms

AO	Announcement of Opportunity
APL	Applied Physics Laboratory
ATLO	assembly, test, and launch operations
CLPS	Commercial Lunar Payload Services
CoMPS	Commercial Mars Payload Services
COTS	commercial off-the-shelf
CP	chemical propulsion
DTE	direct to Earth
EDL	entry, descent, and landing
EELV	Evolved Expendable Launch Vehicle
EIRP	effective isotropic radiated power
ESA	European Space Agency
EscaPADE	Escape and Plasma Acceleration and Dynamics Explorers
ESPA	EELV Secondary Payload Adapter
GAO	Government Accountability Office
GEO	geostationary orbit
GTO	geosynchronous transfer orbit
HPC	high-performance computing
InSight	Interior Exploration Using Seismic Investigations, Geodesy, and Heat Transport
ISP	specific impulse
JAXA	Japan Aerospace Exploration Agency
KISS	W.M. Keck Institute for Space Studies
LASP	Laboratory of Atmospheric and Space Physics
LEO	low Earth orbit
LunaH-Map	Lunar Polar Hydrogen Mapper
LV	launch vehicle
MarCO	Mars Cube One
MASWG	Mars Architecture Strategy Working Group
MAVEN	Mars Atmosphere and Volatile EvolutioN
MEP	Mars Exploration Program
MEPAG	Mars Exploration Assessment Group

MER	Mars Exploration Rover(s)
MRO	Mars Reconnaissance Orbiter
MSR	Mars Sample Return
NASA	National Aeronautics and Space Administration
NLS	NASA Launch Services
NPR	NASA Procedural Requirements
OMB	Office of Management and Budget
PNT	position, navigation, and timing
PSD	Planetary Science Division
PSDS3	Planetary Science Deep Space SmallSat Studies
SEP	solar electric propulsion
SIMPLEx	Small, Innovative Missions for Planetary Exploration
SMD	Science Mission Directorate
STEM	science, technology, engineering, and math
SWaP	size, weight, and power
VADR	Venture-Class Acquisition of Dedicated and Rideshare