A KECK INSTITUTE FOR SPACE STUDIES REPORT

REVOLUTIONIZING ACCESS TO THE MARS SURFACE

A STRATEGY: FREQUENT. AFFORDABLE. BOLD

Revolutionizing Access to the Mars Surface
A Strategy: Frequent. Affordable. Bold.

Study Report prepared for the W. M. Keck Institute for Space Studies (KISS)

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Suggested citation: Keck Institute for Space Studies (KISS), 2022, Revolutionizing Access to the Mars Surface. Culbert, C.J., Ehlmann, B.L., Fraeman, A.A., editors. Final Workshop Report for the W.M. Keck Institute for Space Studies, Pasadena, CA. DOI: 10.7907/d1sm-mj77.

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Cover Image: Chuck Carter/Keck Institute for Space Studies (KISS)

Workshop 1: March 29–April 2, 2021 (convened online)
Workshop 2: September 20–24, 2021
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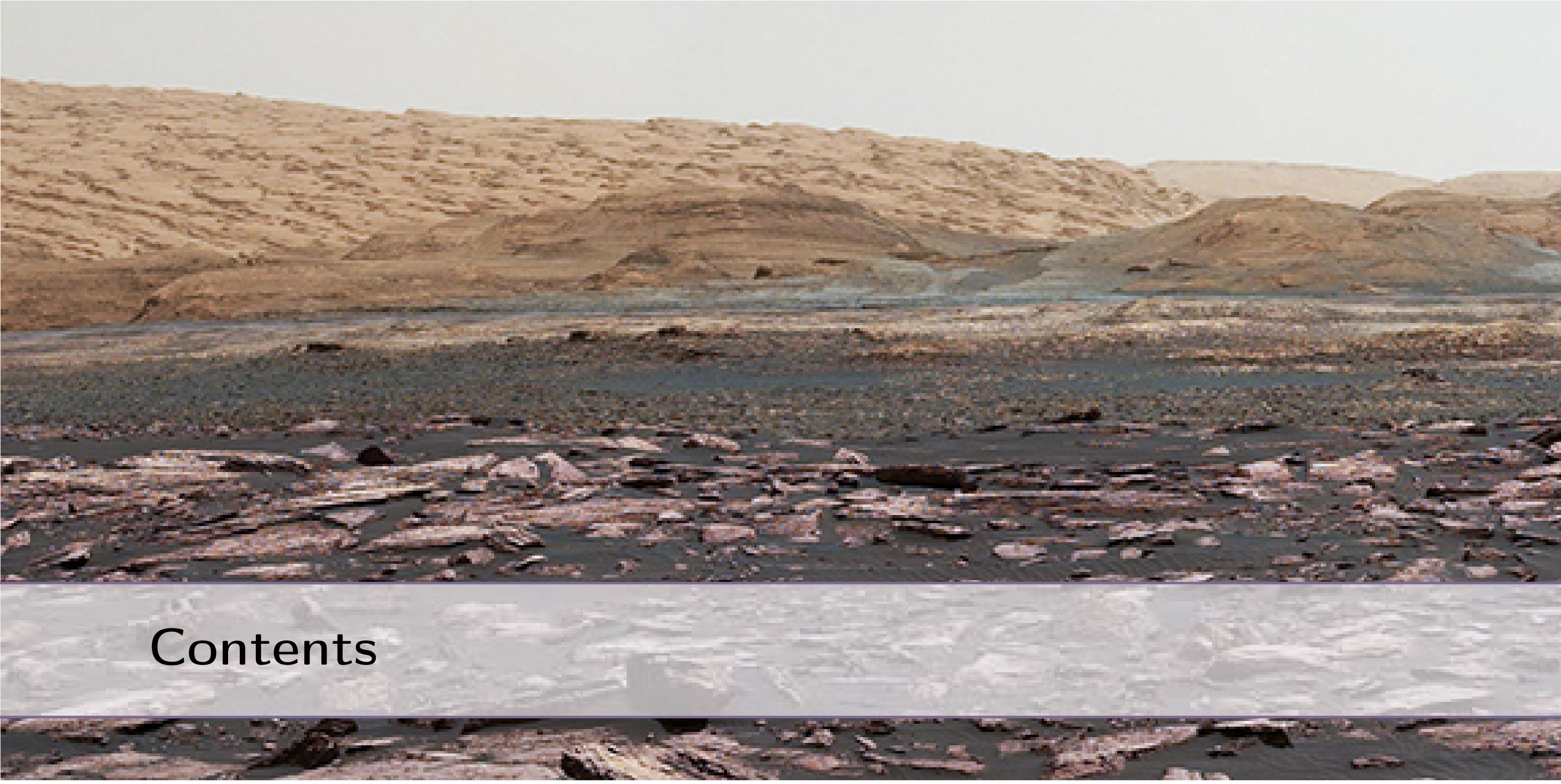

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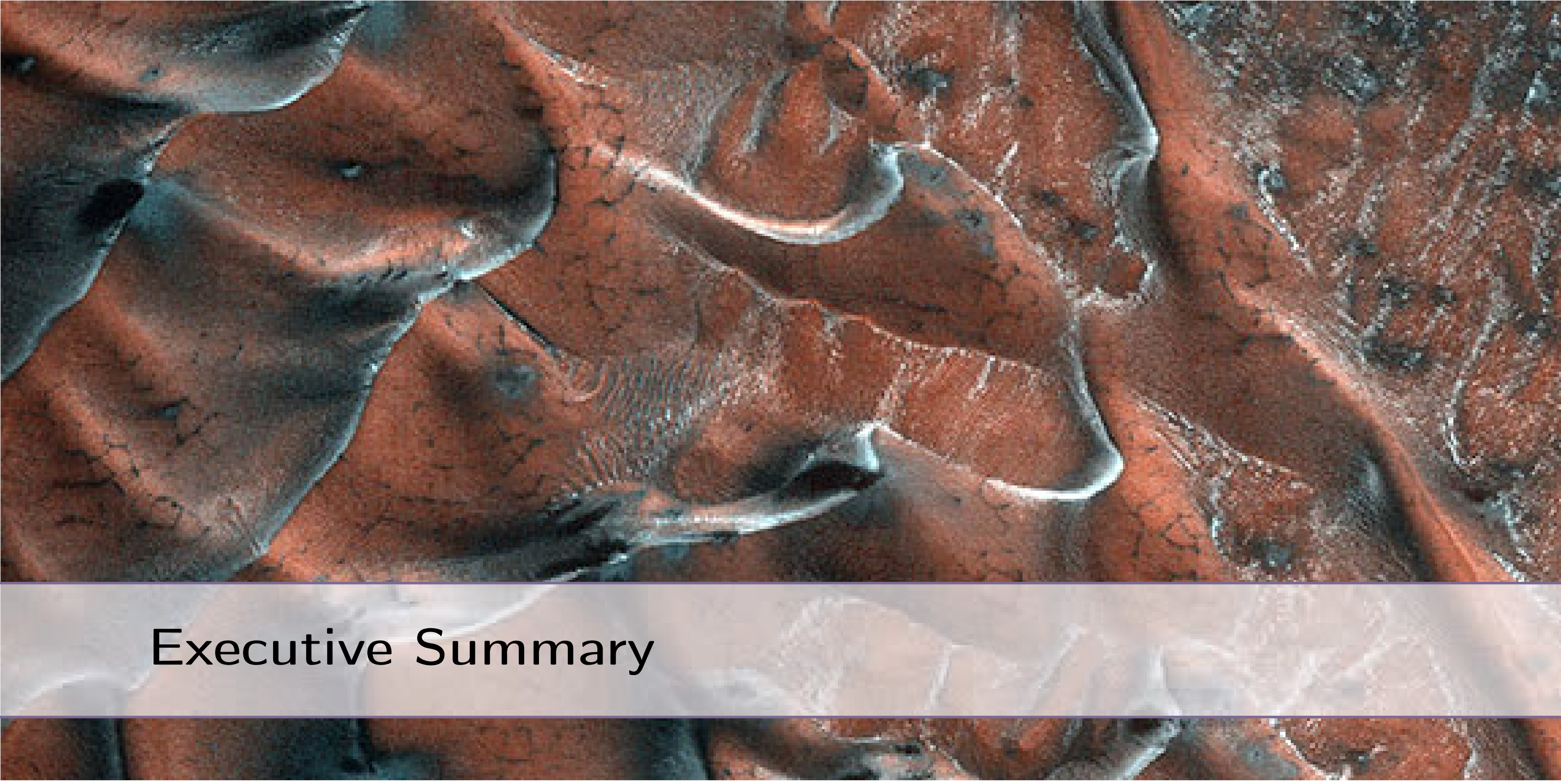


Executive Summary

Twenty-four years after Sojourner took its first wheel turns in Ares Valles, we are on the cusp of a new era for Martian surface exploration. We have had a sustained surface presence by robotic explorers since 2004, along with over a half dozen currently operating orbiting spacecraft. We have imaged from orbit the entire surface at meters-per-pixel scales and discovered thousands of locations that preserve a record of a once habitable world from the formation of the solar system to the present day. Mars has a uniquely accessible historical archive in its rock and ice record and is the best place in our solar system to study the long-term evolution of a habitable terrestrial planet. Mars also has always occupied a unique place in global culture, and it is the only other planet in our solar system which humans could explore (Figure ES.1).

Over the last quarter century, the U.S. has invested in a program of exploration at Mars, enabled by its proximity leading an international effort of scientific exploration in advance of human exploration. More recently, humanity's presence at Mars has expanded well beyond the U.S.'s current program. The U.S., Europe, China, India, and the United Arab Emirates are all currently operating spacecraft at Mars.

As we prepare to conduct the first sample return from Mars, now is the prime time to consider "what comes next?" to ensure continuity of leadership in Mars exploration. The National Academies highlighted the importance of strategic planning of the Mars Exploration Program in the Visions & Voyages Decadal Survey Midterm as well as the 2023–2032 Decadal Survey. As recently highlighted by the Mars Architecture Strategic Working Group report (MASWG, 2020), the depth and breadth of our current scientific understanding of Mars have resulted in a diverse set of priority science questions. Answering these questions will provide

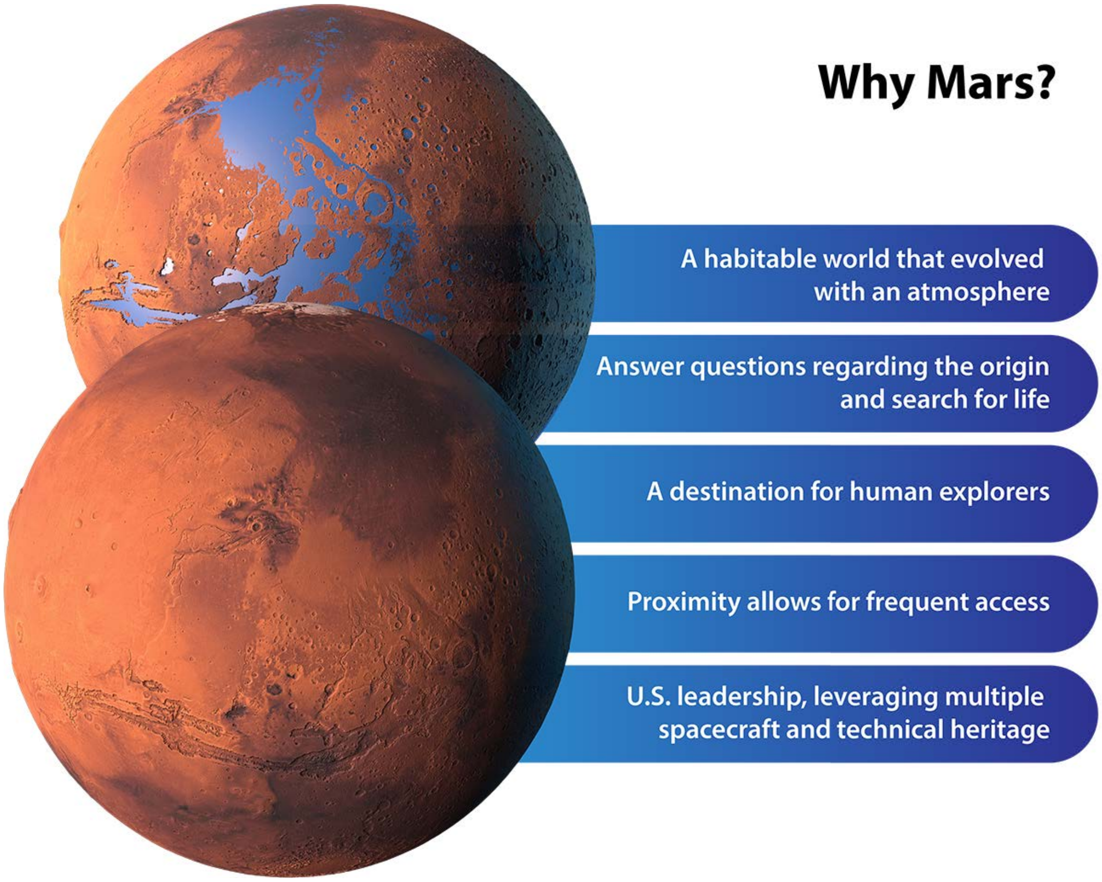


Figure ES.1: Mars exploration is motivated by science, Mars' future as a destination for human exploration, the proximity allowing access, and the heritage systems that enable U.S. leadership in exploration.

an unprecedented detailed synthesis on which Martian environments were habitable, guide investigations of these environments for past or present life, and allow us to decipher the causes, ages and stages of environmental transitions. Such science requires measurements that can only be achieved on the surface and by visiting multiple discrete locations that were not the focus of previous strategies. For example, at the time we landed the Mars Exploration Rovers, we had one location identified from orbit with unique mineralogy. We now have thousands of such sites. The next revolution in our understanding will come from a comprehensive exploration of the diversity that we already know exists.

Recent historical Mars surface missions have cost >$2B ($FY22) or required substantial use of residual hardware or contributed instruments (Section 2). Longer development times and demanding single mission requirements have decreased mission cadence and increased per mission costs (e.g., Dreier and Callahan, 2017). The challenge going forward therefore is not simply to land payloads of various sizes on Mars—this ability has been demonstrated many times over—but to do so at an average per mission cost that enables multiple landings to answer the many scientific questions that require surface access. In situ study of multiple sites with networks or nimble vehicles requires a fundamentally different approach to accessing the Martian surface with platforms that can be delivered to many locations, some requiring mobility and interaction with surface materials.

A strategic programmatic approach is needed to align the incentives for continuity of Mars exploration leadership and more affordable, frequent Mars surface exploration. Technological advances can lower costs. However, assuming an overall NASA budget at Mars similar or modestly higher than present so as to maintain balance in destinations across the solar system, factors in addition to new technical approaches must be brought to bear that fully activate non-NASA stakeholders and their capabilities at Mars. Growing numbers of commercial, international, and academic institutions have capabilities to conduct all or portions of Mars missions. Capabilities in launch and spacecraft development of the private space sector, component and system standardization, and trends in commercial services models for spacecraft are trends that a carefully crafted program can take advantage of to increase Mars surface access without increasing program-level cost to NASA.

Frequent, Affordable, Bold (FAB) is a multi-pronged programmatic approach to improve access to the Martian surface by engaging multiple emerging stakeholders and creating an opportunity to leverage an economy of scale where there currently is none (Figure ES.2). FAB draws from but goes beyond Faster, Better, Cheaper (FBC) by emphasizing a programmatic approach to the target destination rather than putting the onus on single missions. FBC emphasized short mission cycle, reduced mission cost, and higher science return per dollar. FAB emphasizes maintenance of a predictable high cadence of missions, low program cost by changing implementation partnership approaches as well as reducing per mission cost, and bold execution, using new technologies that permit the affordable and frequent elements, compensating programmatically for higher risk.

Programmatic, rather than single mission strategy is essential. It requires defining a finite set of science mission types that can be well-served by shared capabilities of different complexities, effectively providing a roadmap for future collaboration or commercial development opportunities (Section 5.2). Leveraging present trends in the commercial space industry is an important part of the strategy. Also central is changing the relationship between national agencies and commercial providers to one where a subset of Mars Exploration Program missions use a services model, building from small to large landed payload delivery. This allows harnessing the full contributions from all interested parties in Mars exploration (Section 5.4), ensuring continued leadership in Mars exploration and broadening participation across U.S. industry and academia.

Mars Sample Return has primary importance for this decade, and nothing in this strategy is intended to replace or delay MSR. We have identified opportunities to augment and expand on the critical investment in MSR at a relatively low cost with high potential for community engagement and continuity for a robust Mars Exploration Program. A program of FAB-style missions at 2 per launch opportunity fits within a budget of \$100–150M annually during sample return (e.g., 4×\$150M and 2×\$250M Phase A–E costed small spacecraft missions). At the same time, resources would be used to identify and develop commercial partners with needed technological capabilities. After sample return in ~2030, the FAB program might increase to \$250–\$350M/yr, allowing larger mission classes on a 2-year cadence, including up to a \$825M (Phase A–E) Discovery-like mission class with a secondary payload.

The near term-steps to implementing FAB include

- Engaging the stakeholder community with dialog focused on ways to identify where mission activities might align with current commercial interests and near-term technical capabilities and engaging new stakeholders (including from academic institutions and other agencies).
- Working with entities such as MEPAG to develop and maintain a list of priority landing sites and landing site characteristics as well as a science roadmap of MEPAG Science Goals relative to mission types (Appendix A.1).
- Devising instrument development plans that are consistent with early FAB opportunities such as small orbiters and hard landers as well as future fixed landers and mobile assets.

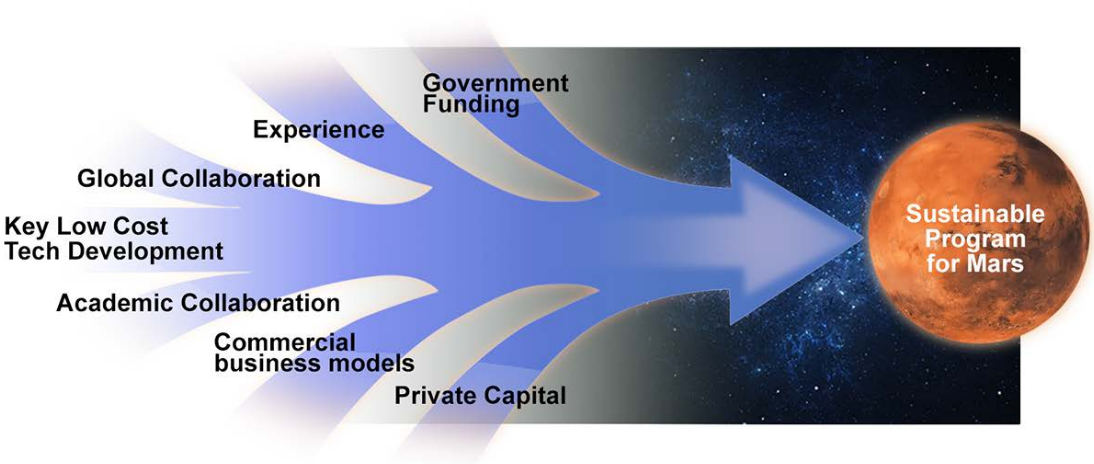


Figure ES.2: Harnessing full contributions from all interested parties is key to a sustained, affordable landed program of exploration at Mars and full realization of economic and societal benefits of the program.

Understanding early instrument technical maturation needs relative to the state-of-the-art and likely progression of system capability development will be important.

- Assessing the present feasibility of commercial approaches to desired capabilities for mission types and determining near-term investments that would enable longer-term program needs for mission types to be met.
- Creating agreements (contracts, grants, Space Act Agreements, cooperative agreements, etc.) for partnering with multiple entities to develop, deliver, or provide services for FAB activities.

Summary of Activities and Report Outline

Under the auspices of the Keck Institute for Space Studies at Caltech, we convened a group of Mars scientists and engineers, representing multiple academic institutions, NASA Centers, and commercial companies in March 2021 to address the challenge of revolutionizing access to the Mars surface. Following a 3-month summer study period where working groups addressed specific programmatic, cultural, and engineering challenges, we then convened a second workshop in September 2021. The report that follows represents the product of the discussions.

We first outline why Mars—and particularly landed access to Mars—is a priority over the next decades of scientific exploration (Section 1). We then review the challenges to achieving increased numbers of missions accessing the Mars surface (Section 2) as well as near-term trends in the space sector that provide means to overcome these challenges (Section 3). We then describe the intertwined elements of the Frequent, Affordable, Bold (FAB) strategy to achieve access (Section 4). Finally, we discuss the means by which a FAB strategy can be implemented, developing similar sets of science mission types and employing a services model that fosters increasing commercial capabilities over a set of the mission types (Section 5).

1. Access to Mars' Surface: Why do we need this now?

1.1 Access to the Martian surface for science

Mars is the best place in our solar system to study the long-term evolution of a terrestrial planet and address questions in the search for life. Earth's first one billion years—the timeframe for the origin and initial evolution of single-celled life—has been obliterated on our home planet due to the action of plate tectonics and erosion. In contrast, Mars preserves abundant ancient crust (also destroyed on Venus), a record of evolution of an atmosphere (lacking on Moon and Mercury) with regular accessibility on a short time frame (not possible with the ocean worlds of the outer solar system). That record shows that Mars was, for at least its first two billion years, habitable with lakes, rivers, groundwater, and hydrothermal systems inhabited today on Earth. Furthermore, Mars has preserved icecaps recording climate variations that are a testbed for comparative planetology to improve our understanding of Earth's own climate processes. Mars has a uniquely accessible archive preserved in its rock and ice deposits.

Mars exploration science and human exploration goals (Mars Exploration Program Analysis Group MEPAG, 2020) and evaluations of the state of the science (MASWG, 2020) highlight key open scientific questions: "What initial conditions make terrestrial planets like Mars and Earth habitable (or not)?," "What were the nature of early habitats on Mars and the causes driving its planetary-scale environmental change?," "What are the reservoirs of water and ice, how do they form, and how have they changed with climate fluctuations?," and "Did life originate on Mars, and if so, how, and is Mars inhabited now?"

A subset of these questions will be addressed by Mars Sample Return, which is and should be the highest priority in Mars exploration for the next mission. Nonetheless, decades of orbital and *in situ* exploration have highlighted the geologic diversity of Mars. A program of measurements at the Martian surface at multiple sites is necessary to enable the step change in answering these scientific questions about Mars' evolution and search for life (e.g., Dehant et al., 2012; Diniega et al., 2021; Edwards et al., 2021; Ehlmann et al., 2016, 2017a,b; Niles et al., 2012; Rafkin et al., 2009; Wray, 2012). Different places on the surface record different processes and different time slices of Mars' four billion year history (Figure 1.1; Appendix A.2). Lessons from the study of our own Earth highlight the importance of exploring multiple sites to understand and distinguish the influence of both local and global phenomena, and that learning about planetary processes requires integrative study of the rock and ice record across time and space.

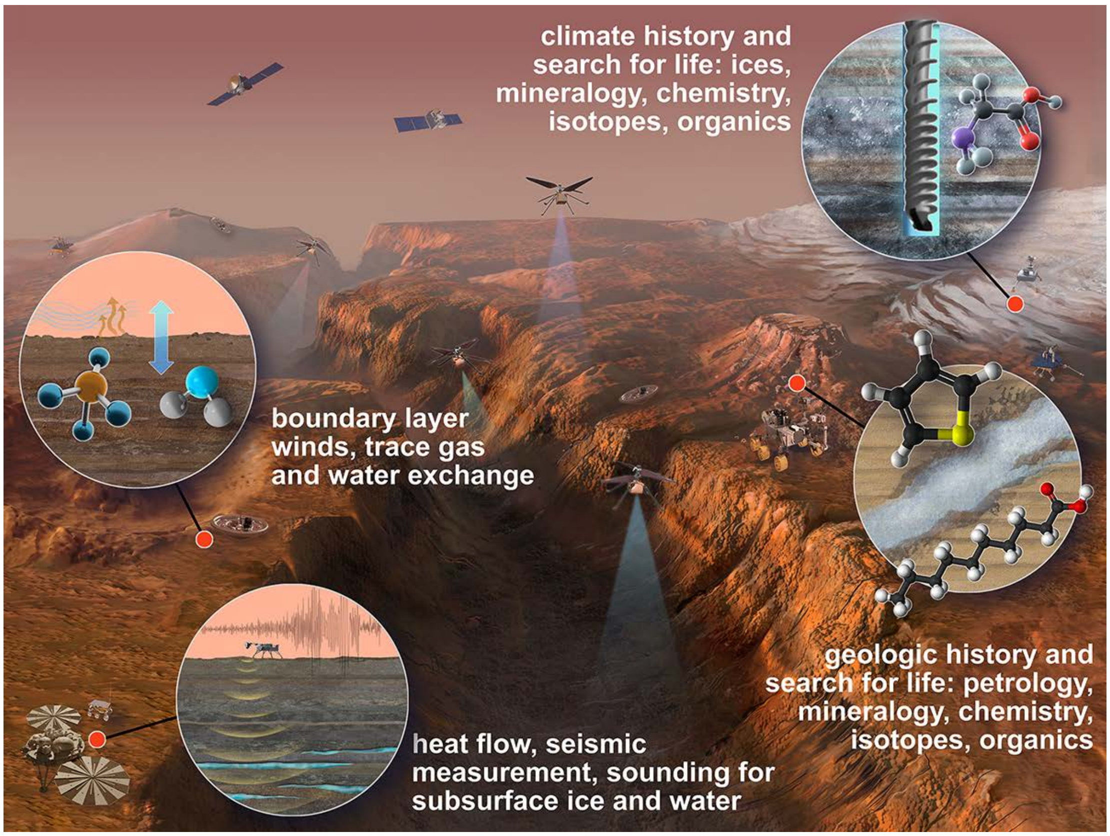


Figure 1.1: Crucial scientific measurements for understanding the Mars system require access to and interaction with the Mars surface. Access to and interaction with rocks and ices is needed for measurements of texture, chemistry, mineralogy, isotopes and organics content at sub-centimeter scale. Landed measurements are required for boundary layer winds and measurements of exchanging gases (e.g., CH_4, H_2) at the surface-atmosphere boundary. Priority measurements of the subsurface that can only be accomplished with landers include sounding for water, heat flow measurement, and detecting Mars quakes to resolve subsurface structure at regional scales, performed from a variety of platforms.

Needed measurements require *in situ* data that achieve mm- to µm-scale resolution of rock and ice textures, quantitative compositional analysis (chemistry, mineralogy, isotopes) at high precision, and interaction and processing of surface and subsurface materials not achievable from orbit (Ehlmann et al., 2016). For example, deciphering recent (Amazonian) climate change requires detailed compositional information from polar and mid-latitude ice deposits at discrete locations on the poles (Becerra et al., 2021; Smith et al., 2020) and a few of the dozens of locales where exposed ice is observed or is predicted to be within a few centimeters to meters of the surface (Dundas et al., 2018, 2021; Piqueux et al., 2019). Improving knowledge of Martian interior evolution, magnetic field history, modern atmospheric processes, and surface-atmosphere interactions requires networks of meteorological and geophysical instruments on the Martian surface. Tracing the history of climate and habitat potential of Martian environments requires measurements of *in situ* petrology, texture, mineralogy, chemistry and isotopes in discrete mineral phases. Appendix A.1 outlines some of the key measurements.

The Mars Architecture Strategy Working Group (MASWG, 2020; their Finding #7) highlighted the growing importance of such *in-situ* data to address science objectives across a range of mission classes and the importance of investment to make such surface access affordable (Table 1.1). In their report, the size classes were defined by cost. There is a significant role to be played by small spacecraft, including orbiters and landers, as small spacecraft improve. However, small spacecraft capabilities alone are unlikely to realize all the important measurements of *in-situ* science, some of which require systems to manipulate the surface (deploy instruments, acquire and process samples) and carry large instruments (e.g., mass spectrometers and integrated drill instrument/science packages). A range of landed mission types—defined in terms of capability (e.g., payload mass, mobility)—are required to achieve the important science accessible only at the Mars surface (Appendix A.1).

Science Goal Mission Element	M-Arc	SSc	DSc	NFc	FLG
Orbit-based characterization of atmospheric circulation, transport processes	3,4				
Transport of dust/aerosols and their relationship to atmospheric escape and climate	4				
Low-altitude global magnetic field survey, gravity mapping	2				
Environmental transitions in the ancient record by high resolution orbital imaging spectroscopy	1				
In-situ geophysics (subsurface ice/water w/ resistivity, GPR; seismology, magnetism)	2				
In situ surface-atmosphere boundary layer interactions (trace gas measurements)	4				
In situ, mobile geological explorers for characterizing ancient habitable environments, environmental change, organics detection	1				
Global orbital radar mapping of ice reservoirs	3				
In situ mid-latitude ice sampling for characterization	3				
In situ polar layer deposit climate record determination	3				
In situ geochronology for Martian and solar system chronology	1,2,3				
In situ life/organics detection in Martian deep subsurface	1,2,3				

Possible or partial priority science at this class

Achieves priority science at this class

Table 1.1: The MASWG report identified numerous science goals that specifically require *in situ* measurements that span a variety of mission classes to the surface. These spanned small spacecraft (SSc; \$100–300M), Discovery (DSc; \$500M), New Frontiers (NFc; \$1B), and Flagship (FLG; >\$1B) cost classes as defined under traditional program architectures. Key to revolutionizing access to the Mars surface, enabling progress on the science identified by MASWG, is achieving the measurement capabilities of the mission element at a lower-than-traditional price point.

1.2 Continuity of progress and presence of U.S leadership at Mars

For the past 60 years, the United States has derived significant prestige from its successful space program, especially the Mars program, where no other country had successfully landed on the surface until 2021. However, other organizations and nations (e.g., ESA, China) are closing that gap with multiple countries delivering Mars orbiters and the successful 2021 Chinese rover landing. Indeed, as reinvigorated programs of human exploration look to the Moon and beyond, Mars remains a key destination for exploration. Other nations have the motivation and capability to continue to improve their Mars-relevant technology. As a destination for U.S. human explorers (e.g., White House, 2021), U.S. progress requires being at the vanguard of this growing international interest.

Continued presence at Mars and leadership in its exploration, requires that the U.S. broaden its portfolio of future Mars missions beyond the flagship-class Mars Sample Return program to include regular exploration of the Mars surface, effectively committing to a continuity of U.S. landed presence. This will result in more continuous coverage of the program in public attention, involve more people across the country in the science and technological innovation required for exploration (see Sections 3.2 and 3.3), provide regular opportunities to demonstrate technological progress, increase the depth and breadth of scientific data, maintain U.S. leadership at this key long-term destination of enduring interest, enable opportunities for growth of the commercial space sector, and grow the skilled workforce, expertise, and organizational infrastructure necessary to support Mars exploration.

2. The Challenge

In our first workshop and summer studies, we examined historical landed Mars missions as well as proposed technological approaches for future Mars missions. At an element level (launch, cruise, EDL, landed elements) and at a subsystem level within the landed element, we broke down current and likely future capabilities to Mars. Working from science objectives, we examined implications for mobility, EDL, cruise, and launch, seeking those technologies that would open up more of the surface for exploration but also enable reduction of per unit mission costs. This examination reveals a combination of technological innovation as well as programmatic change is required to produce a step change in our ability to access the Mars surface.

2.1 Historical Mars Surface Missions

Historically, half the missions to Mars have ended in failure, but in the modern era, the outcome is typically success. For landed missions, 10 of 15 attempts at Mars landings have been successful (e.g., Lakdawalla, 2018, 2020). The U.S successfully landed two 600-kg Viking landers, deployed from the Viking orbiters, in 1976. The 92-kg Mars Pathfinder and two MER (each about 500 kg) landed successfully with aerobraking, parachute and airbags. Meanwhile the Mars Polar Lander (MPL) and its Deep Space 2 impactors were lost. Phoenix and InSight both landed roughly 350 kg to the surface. The 900-kg Curiosity rover and 1030-kg Perseverance rover were landed with the sky crane system. ESA lost its Beagle lander and Schiaparelli landers, which employed airbags and rocket-assisted descent respectively. China's Tiawen-1 mission landed its 240-kg Zhurong rover in 2021.

Historically, development costs in FY22 dollars for successful NASA missions, not including launch vehicles, ranged from \$370M for Pathfinder and the Sojourner rover to \$2.8B for the Mars Science Laboratory Curiosity rover (Table 2.1; Figure 2.1). The initial challenge of landing on Mars was addressed by Viking and, after a long hiatus, 4 landed missions were conducted at high candence using similar aeroshell technology, 3 successfully, landing 4 spacecraft on the Martian surface over 1997–2007 (Pathfinder, Spirit, Opportunity, Phoenix). MER was a successful mission of two identical rovers that leveraged multiple builds to lower per unit costs, increase and diversify the science achieved, and lower programmatic risk of single mission failure. InSight competed successfully within the Discovery program with a single station seismometer, different from prior network lander concepts for Martian seismology (To date, a network mission has not flown, in spite of substantial enthusiasm for its science, in part due to cost challenges for multi-lander access to the surface; Appendix 3). Directed missions then moved away from multiple builds in favor of custom designs to carry laboratory equipment and hardware for sample manipulation, driving single rover costs to levels (>\$2B/unit) such that multi-unit builds became programmatically cost-prohibitive. In the late 2000s through 2020, two similar rovers (Curiosity and Perseverance) were built in sequence, separated by 8 years. Recently, rising costs of launches, longer development times, and fewer missions in the pipeline were identified as potential threats to the U.S. Mars Exploration Program (Dreier and Callahan, 2017).

Mission	Type	Year	RY $M	FY22 $M	Dev. Costs, FY22 $M	Dev. Duration, yrs	Launch Services Cost, FY22 $M	Mission Ops Costs, FY22 $M	Mission Ops Duration, yrs
Viking 1 & 2[a]	Lander (2) + Orbiter (2)	1975	$1,058	$7,244	$6,165	7	$551	$528	4, 6
Pathfinder	Lander with Rover	1996	$262	$487	$371	4	$90	$26	0.25
Mars Polar Lander (MPL) + Mars Climate Orbiter (MCO)[b]	Lander + Orbiter	1999	$291	$514	$336	4	$151	$27	—
Mars Exploration Rovers (MER)[c]	Rover (2)	2003	$1,080	$1,595	$1,001	4	$150	$444	6, 15
Phoenix[c]	Lander	2007	$420	$575	$441	5	$118	$16	1
Mars Science Laboratory (MSL) Curiosity Rover[c]	Rover	2011	$2,965	$3,691	$2,839	10	$256	$596	10
InSight[c]	Lander	2018	$826	$936	$683	8	$185	$68	5
Mars-2020 Perseverance Rover[c]	Rover	2020	$2,757	$2,956	$2,395	8	$267	$297	3

Table 2.1: Costs of Mars landed missions, normalized to FY22 dollars. Development costs include formulation and implementation. Mission operations costs include primary mission and extended mission operations. Original data compilation from the Planetary Society (2021) and references therein, here scaled to common FY22 dollars.

[a] Cost includes $1.5B Dev for 2 orbiters; Ops costs are for all 4 spacecraft
[b] Orbiter and lander costs not differentiated; launch costs include 2 launch vehicle; both missions failed
[c] Contributed instrument costs are not included

Examining mission-level vs. programmatic-level cost aspects to enable surface access at lower price points is thus central to any plan for increased science at the surface. The historical range of costs suggests that a systematic approach to increasing the number of craft on the Mars surface can be done because lower per-mission costs and higher cadences have been a characteristic of past decades (Figure 2.1).

2.2 Getting to Mars: Launch, Cruise, and Propulsion Systems

Delivering missions for landing on Mars requires launch and then a propulsive cruise stage. Launch costs for recent Mars missions have been $75–270M (Figure 2.2). The cruise stage provides propulsion for trajectory maneuvers, telecom, and power, comprising 8–30% of the mission cost. Launch cost is a significant mission cost driver for lower cost missions

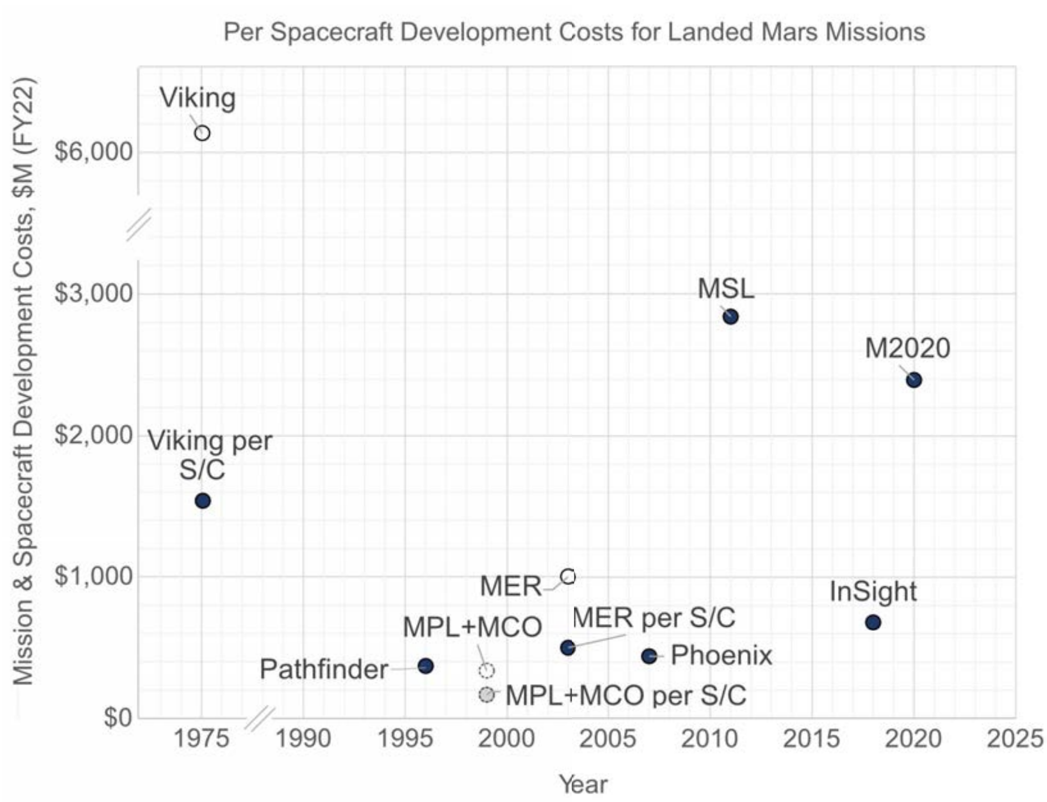


Figure 2.1: Spacecraft development costs for Mars missions to date with all costs converted to FY22 dollars. Original data compilation from the Planetary Society (2021) and references therein here scaled to common FY22 dollars.

(Table 2.1), e.g., launch cost was 20% of the development cost for Mars Pathfinder, Phoenix and Insight and an even greater percentage for the combined Mars Polar Lander/Mars Climate Orbiter development.

Launch services have been rapidly evolving over the last decade with booster recovery and reusable rocket components, interface standardization to enable a robust rideshare market, market forces driving new commercial entrants, the rise of small launch capabilities that are geared primarily to service terrestrial markets, and the disruptive effort of SpaceX in developing affordable, heavy-lift launch for Elon Musk's goal of a permanent human presence on Mars.

For Mars missions with a total mass in the 50–400 kg range, it is realistic to assume a number of mechanisms to enable reduced future launch costs, potentially in the low to mid-$10s M (see Box 1). However, launch alone is not sufficient to enable Mars trajectories. Also key to enabling Mars access via rideshare or small launch vehicles that do not directly insert the spacecraft onto a Mars transfer trajectory are propulsion systems that provide significant ΔV

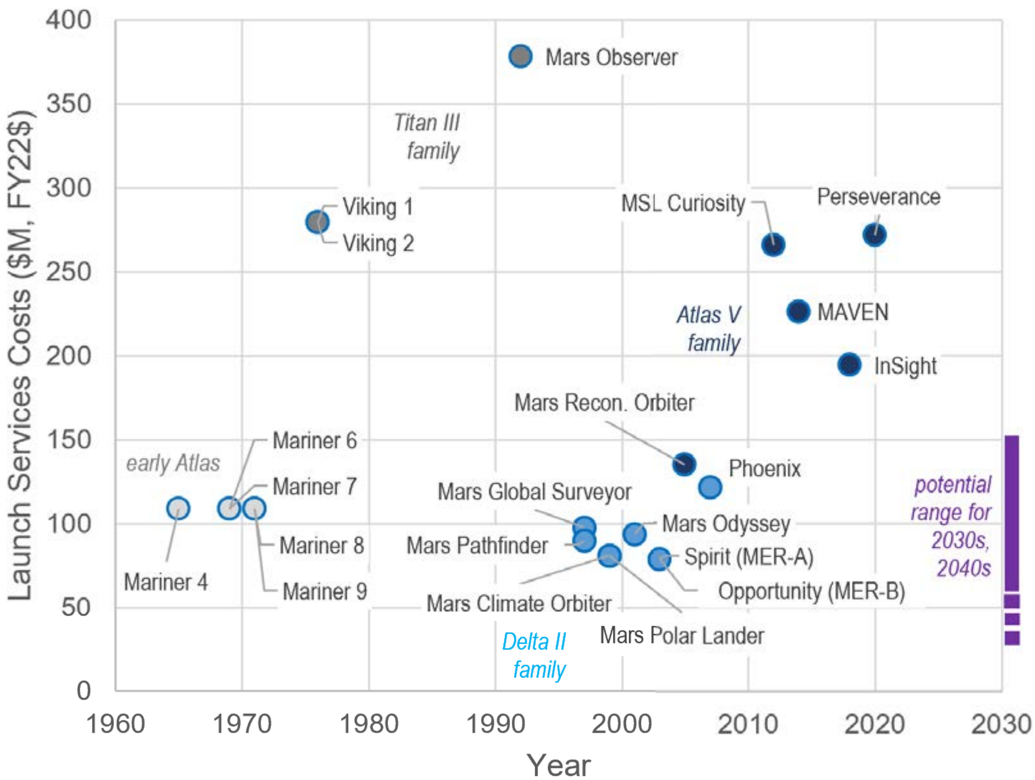


Figure 2.2: Launch vehicle costs for Mars missions, converted to FY22$ show the potential for ~$100–200M savings relative to recent missions, given historical prices and the anticipated potential for more competitive small and large launch markets (see Box 1). Original data compilation from the Planetary Society (2021) and references therein.

to complete the transfer to Mars. Low-cost, high ΔV systems that do not exceed mass-limits are an important area of technology development to enable small spacecraft access to Mars without a direct launch.

On the other end of the spacecraft mass spectrum, a major opportunity may exist for enabling large spacecraft at Mars, if the promise of the SpaceX Starship's 100 metric ton delivery capability is realized (Bender, 2021; Musk, 2018). The target per kilo to Earth orbit is <$100/kg, a factor of 10 lower than at present. This would enable larger spacecraft—with ability to incorporate larger, already-existent propulsion systems with substantial ΔV—to be readily staged in LEO or GEO for travel to Mars. Starship has also proposed future ability to land on Mars (Section 2.3). Key to taking advantage of lower costs for high mass capacity launch is lowering per-mission costs of the landed asset(s) and its instruments.

Box 1 A Tale of Emerging Launch Capabilities at Two Mass Points

A key juncture in planning surface missions is consideration of launch outlook for different mass classes.

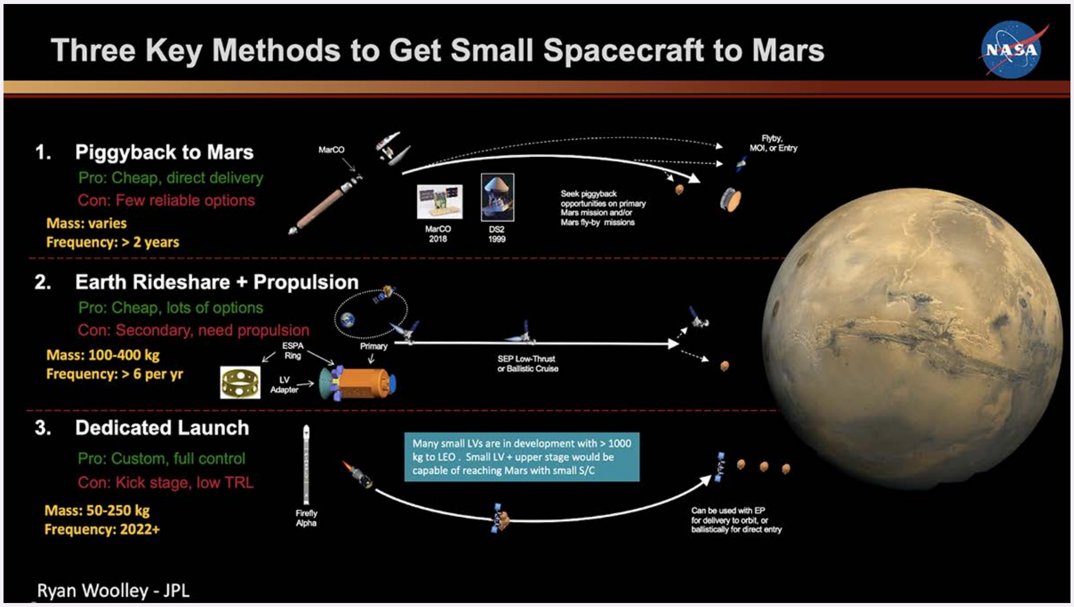
Low-mass Mars missions. Looking to the next decade, the cost for launches of small spacecraft are likely to continue to fall for LEO and GEO due to trends in the rideshare and the small launch market. Several companies also tout deep space capabilities, with advertised small-launch price points to the Moon of $10–12M (RocketLab, ABL, Firefly). Consequently, three methods have opened to get ~50–400 kg missions to Mars (further detailed in Woolley et al., 2021).

1. *Rideshare or ride-along with a Mars-bound primary.* The twin MarCO cubesats demonstrated this approach, separating at launch from the InSight primary and independently performing flybys of Mars. When flying independently, launched with a Mars mission or a Mars flyby, a key technical requirement is having sufficient ΔV on the small spacecraft to target and achieve the desired entry conditions for a lander or final orbit for an orbiter. Flight with the primary and delivery to orbit, or separation prior to orbital insertion or entry is also an option, though would require intimate coordination with the primary mission. While this method is low-cost and straightforward, suitable Mars-bound missions are presently infrequent. MSR elements are the next near-term opportunity, anticipated in ~2028.

2. *Rideshare to an Earth orbit.* Typical rideshares will make use of an ESPA ring, which carries limitations on mass and volume available (Moog Space and Defense Group, 2018). The total ΔV from Earth orbit to Mars can be very high (>4 km/s for impulsive maneuvers, or >10 km/s with low-thrust), which is challenging for a small spacecraft because much of the mass must be dedicated to the propulsion system and propellant. Though less frequent than low-Earth orbit (LEO) launches, it is far preferable to start from a higher-energy orbit, such as geosynchronous transfer orbit (GTO) or lunar transfer orbit (LTO) as this will greatly reduce the required ΔV and trip times for a subsequent Mars transfer.

3. *Dedicated launch vehicle.* This is the traditional method for missions to Mars and allows for the most flexibility in selecting launch conditions and dates. Typical launch vehicle costs have historically been prohibitively high for cost-constrained small missions (Figure 2.2, Table 2.1). Driven by markets in Earth-orbit, a large number of companies are now competing to develop smaller launch vehicles with much lower costs, which in some cases can be comparable to the cost of being manifested as a rideshare. As a rule-of-thumb, approximately 10–20% of the mass launched to LEO could be sent on to Mars, given an appropriate kick stage, with

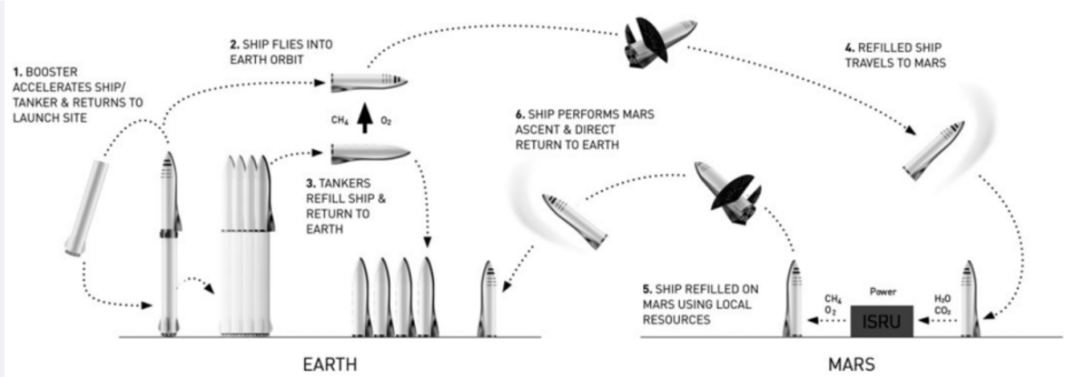
the remaining mass dedicated to propellant and the mass of the propulsion system itself.



(Figure courtesy R. Woolley; see (Woolley et al., 2021))

High mass Mars missions. The SpaceX Starship development promises more capability to deliver very high mass payloads, potentially breaking the historically strong correlation of mission cost to mission mass (Appendix A.6). Central is the use of high volume, large mass (100 metric ton) reusable launch to and from LEO. Starship is a two-stage vehicle with a SpaceX Super Heavy Booster first stage and Starship as the second stage; both are fully reusable. An on-orbit refueling system supports access to destinations beyond Earth. Such a large payload capacity is unprecedented for planetary science and could technologically enable more than one large mission to the Martian surface per launch.

The first set of Starships launched to Mars will be uncrewed and are intended to demonstrate the capability to successfully launch from Earth and land on Mars with human-scale lander systems. These uncrewed vehicles will provide the opportunity to deliver significant quantities of cargo to the surface, including the potential for delivery of mobile robotic assets that could be used to conduct planetary science research (Heldmann, 2021). This is an opportunity for mission delivery that a Mars program could capitalize on for priority science with advanced program planning for surface missions that include high mass systems or multiple lower mass systems.



(Musk, 2018)

2.3 Entry-Descent-Landing (EDL)

The saying that Mars' atmosphere is "too thick to ignore but too thin to be useful" reminds us that the atmosphere of Mars introduces special challenges, necessitating a different EDL approach to airless bodies or Earth reentry. Challenges and costs in reproducing Mars-relevant environments for hypersonic and supersonic systems test also slows development of new approaches (Braun and Manning, 2007).

Historically, Mars landed missions use a variety of technologies to transition from hypersonic atmospheric entry velocities to a survivable touchdown on the surface, including heat shields, parachutes, retro propulsion, and landing impact absorption. Precision of the landing, complexity of the system, tolerance to small scale hazards, and fuel mass required for landing all trade off. Guided entry systems, radar systems and range triggered parachutes enable shortening the long axis of the landing ellipse. Hazard avoidance (a divert maneuver) and terrain relative navigation by onboard image mapping allow safe landing in rough terrains, enabled by onboard processing, and more fuel mass. At both Mars and the Moon, these precision landing technologies are becoming more routine, enabled by onboard image or lidar acquisition and processing (partly driven by autonomy in the auto industry; Section 3.1) as well as thrusters to execute descent correction maneuvers. Precision landing is desirable but it is not required for some mission types (Section 5.2).

EDL drives the overall mass delivered to Mars vicinity, with just ~15–30% of the mass ultimately used in furthering scientific exploration (Table 2.1; Braun and Manning, 2007). Finding ways to significantly lower EDL mass has bearing to lowering overall mission cost.

	Viking	Pathfinder	MER A/B	Phoenix	MSL	InSight	M2020
Entry Capsule							
Diameter (m)	3.5	2.65	2.65	2.65	4.5	2.65	4.5
Entry Mass (kg)	930	584	840	602	3151	608	3440
Landed Mass (kg)	603	360	539	364	1541	358	1600
Science Enabling Mass (kg)	244	92	185	167	899		1050
Instrument Payload (kg)	91	8	9	59	84	50	59
Landing Altitude (km)	-3.5	-1.5	-1.3	-3.5	-4.4	-2.6	-2.5
Terminal Descent Approach	Retro Propulsion	Airbags	Airbags	Retro Propulsion	Skycrane	Retro Propulsion	Skycrane

Table 2.2: Most mass delivered to Mars is for EDL with only ~15–30% utilized for scientific exploration (table adapted from Korzun et al., 2019; and landing site press kits). Science-enabling mass is the "useful mass" of Braun and Manning (2007): the payload, surface interaction and mobility systems, and subsystems needed to support them. The 2021 Zhurong rover had a science-enabling mass of 240 kg. Landed mass for MSL and M2020 includes skycrane mass.

We examined whether powered descent lunar systems could be adapted for Mars, perhaps then using such systems to hop and provide mobility while on the surface. While the design would not preclude 'hopping' capability, we found that the fuel requirements for orbital insertion and then direct descent seem undesirable, although this warrants further study, particularly if paired with orbiters (e.g., Viking, Tianwen-1).

We examined minimal EDL approaches like hard landers or air-deployed helicopters. These are very promising for certain mission classes and worthy of pursuit. Hard landers attempt to minimize cost by keeping mass very low, eliminating the parachute, retro propulsion, and associated descent sensors and electronics, and using a crushable impact attenuator for landing. This limits payloads to those with capacity to survive landing decelerations on the order of 1,000 Earth g's (Barba et al., 2021). Hard landings also have a science payload mass limit of ~5 to 10 kg. In the case of a next generation Mars helicopter, a mid-air deployment is envisioned to remove the need for an EDL system entirely (Delaune et al., 2020; Rapin, 2021). The physics of powered rotorcraft flight in the thin Martian atmosphere limit the payload to a few kilograms for helicopters of practical size. There are a set of science questions and measurements that can be addressed within these Pathfinder/MER sized payloads, but more mass is desirable for interaction with martian materials and select types of instruments (e.g., mass spectrometers).

Multiple approaches are being considered for landing much larger systems on Mars, such as deployable decelerators, inflatable aeroshells, retrograde propulsive systems that have the potential to increase the mass delivered to the surface. However, missions larger than the ~1000 kg Curiosity and Perseverance require aeroshells larger than can be accommodated by current rocket fairings. Alternatively, SpaceX is planning that the same orbital entry and landing capabilities used to make Starship a fully reusable Earth orbit launch system will also be used to land large payloads on Mars. This includes flying a high-lift hypersonic entry trajectory, and the use of aerodynamic control surfaces and engines to maneuver and decelerate the vehicle for landing (Musk, 2018). Such large payload capacity to—and potential for return to Earth from—the surface of Mars would provide a truly revolutionary means of surface access for planetary science (Heldmann, 2021). If these capabilities are realized, the combination of large mass and low delivery cost could open up new possibilities for conducting large Mars surface missions in an affordable fashion, and breaking out of the paradigm that large mass must mean large cost.

2.4 Landed Elements

Payload mass and sophistication as well as requirements for mobility, surface interaction, and sample manipulation all trade to determine the size and nature of the landed element required. Instrument and surface manipulation mass fractions have historically been a very small fraction, <10% of the total mass of mobile missions (Table 2.2), whether solar or nuclear powered. Simple lander systems with a higher mass fraction for scientific instrumentation can achieve certain science goals while other science goals require mobility and extensive surface interaction (see Section 5.2). Understanding what could raise the mass fraction for science or lower cost per mass is a key to affordable access to the surface.

Mechanical subsystems are among the most expensive subsystems on the rover but are essential for enabling mobility and interaction with the Martian near surface desirable for many science goals. Technical approaches for improving mobility include greater autonomy via onboard processing and navigation, simplification (6 to 4 wheels), and more cold-tolerant systems for reduced power. Rather than parts, labor dominates this subsystem to develop new approaches to verify and lower risk.

Although mass can be an indicator of cost, attention must also be paid to minimizing the number of discrete payload interfaces and different types of interfaces (e.g., interfaces to the lander avionics), eliminating subsystems (e.g., impacting landers without parachutes and propulsion), simplified or reduced mechanisms (e.g., avoid deployments or articulations where possible), and looking for commonality in parts and components that minimize special development. All of these factors play into the scope of vehicle testing, which will drive cost as the amount of verification testing increases.

2.5 Potential Opportunities to Overcome Challenges

The result of our study of historical and near-term expected technologies is that there is no capability barrier to achieving increased access to the Mars surface. The key challenge is achieving access at costs at significantly less than \$1B/mission, given present procedures, particularly as mobility is required and payload masses sizes grow beyond ~5kg. Key findings from historical and near future missions include

- We see opportunities for incremental cost reduction under existing approaches for all mission classes but not radical ($>2\times$) reductions.
- Historically, surface missions have been conducted at far less than \$1B/unit cost, indicating that it is possible to do so again.
- Lowering launch costs could save \$10s–low \$100s M/mission.
- The mechanical subsystem of the lander costs the most in terms of hardware, but labor still dominates cost.
- Whatever reduces labor helps cost, e.g., simplicity, standardization, reuse, modularity/automation in testing.
- Thinking across multiple missions, types of spacecraft, and target bodies can maximize benefit for technology and cost by reducing non-recurring engineering and parts common across missions.

These inform the strategy articulated in Section 4.

3. The Opportunity

3.1 Growing Commercial Capabilities and Markets

We are at a natural juncture to leverage innovation in the space and technology sectors to enable a program of Mars surface access that grows the U.S. commercial space sector. In 2021, the number of satellites launched, the use of personal electronics, and the number of technology-driven startup companies are at record highs. Private investment in space companies has risen to unprecedented levels, including large venture capital outlays, novel investment vehicles, and the personal capital of billionaires such as Elon Musk and Jeff Bezos. Social and entertainment media may create new opportunities to tap into the excitement of space exploration. For the first time, the incentives of all these different stakeholders are aligning in a way that can be harnessed for pushing the bounds of space exploration, including at Mars.

The past decade has seen massive increases in commercial sector space capabilities and decreases in cost of key aspects. This has included new entrants and the introduction of reusability in the launch arena, deployment of large constellations of Earth observation and communication satellites, private human orbital and suborbital spaceflight, and the transition of ISS resupply and crew exchange to commercial vendors. In many cases, these activities have leveraged technologies and approaches demonstrated in other sectors for use in space. Spurred in part by the Google Lunar XPrize and continued through a number of initiatives including NASA's CATALYST and Commercial Lunar Payload Services (CLPS) programs, a number of companies are currently poised to begin robotic lunar surface missions. NASA's Artemis Program is making use of commercial providers for key aspects of human lunar missions, including the demonstration of capabilities that can be leveraged for missions to

Mars (Box 2). While significant strides will need to be made in reliability and performance, the track record of commercial companies in low Earth orbit suggests they will eventually achieve more aggressive goals.

Combined, these changes present a new and enabling opportunity for the Mars program to balance its mission portfolio by leveraging commercial capabilities and approaches. Partnering with the private-sector can also help bring to bear additional financing and technical capabilities (see Section 5.4) to enable affordable missions to Mars, allowing for increased scientific discovery within NASA's overall planetary science budget. A series of low-cost missions, anchored by NASA funding but augmented through partnerships, would balance the ongoing Mars Sample Return flagship program. Mission requirements at Mars would take industry capabilities developed for the CLPS and Artemis programs and additionally prove them out for use on Mars. Broadening the planetary destinations for investment would grow the business base for lunar exploration technology and thereby feed forward to increase the overall support and capability for planetary missions.

Box 2 The Time is Ripe: Leveraging & Growing Industry Activity

Innovation in space is rapidly changing. This section presents a partial list of key technologies and developments that can be leveraged to develop cost-effective ways to explore the Red Planet.

Autonomous Systems and Mobility. Self-driving cars and autonomous vehicles have been under development by DARPA and other agencies since the 1980's. Increases in computing power have allowed the underlying algorithms to be deployed in products varying from remotely piloted drones (where fast loop closure for flight dynamics is split from pilot interactions) to automotive applications (where faster-than-driver reactions are enabled for safety features). The Ingenuity helicopter on Mars validated these technologies in a space environment. While not all aspects of these autonomy advances can be used in space applications, identifying opportunities to reuse autonomy software or modify for use on space avionics could yield high value.

Electronics. The increase in computing power available in a small form factor is apparent every day to any smartphone user. Those reductions in size also benefit spacecraft and space systems. Smaller avionics components that require less power lead to smaller systems and spacecraft overall, reducing the cost of sending those systems into space. The use of these modern devices has been limited at Mars due to concerns with environmentally induced bit errors coupled with heritage hardware/software error correction architectures. Advances in fault tolerant hardware design, redundant systems, and advanced software architectures may enable commercial parts to be used 'off the shelf,' avoiding expensive redesign and reoptimization.

Another valuable technique for using commercial electronics would be for an agency such as NASA to pre-qualify a set of commercial processor parts that could be used across industries. A program such as this could be applied in a similar TRL-raising strategy to a MATISSE or PICASSO instrument development program, but at the part level.

Simulation and Test. Flight system testing of a complex, one-of-a-kind vehicle is expensive, particularly in the case of optimized performance with intricately timed hardware/software interactions. In order to test all potential fault scenarios, the flight vehicle and its associated test beds are exercised 24 hours a day in the months leading up to launch. For small Mars missions, there may be opportunities to reduce these V&V costs by taking advantage of simpler designs with fewer fault tree branches. The more regular cadence may also allow flying a flight system more than once to benefit from previous V&V efforts. Advances in simulation capabilities such as digital twins may also allow less reliance on physical tests to meet V&V goals.

Moon to Mars. A program taking advantage of commercial developments for Mars exploration should take advantage of the current work being done to explore the Moon. We make this suggestion, fully recognizing that there are many differences between the two surface environments, but also being cognizant of the similarities. For example, a mechanism designed to be robust to lunar dust may be overdesigned for Mars, but an electronic part used at the Moon may have similar radiation hardness characteristics. The recommendation is to start from existing capabilities and apply them judiciously. Additionally, to achieve low cost one's design point may have to be acceptable rather than optimal.

3.2 Mechanism for Broadening Cooperation with Emerging Space Powers

From the perspective of orbital dynamics, Mars (and the Moon) are relatively accessible and thus occupy a special role in solar system exploration as "gateway destinations" for emerging space powers, demonstrating deep space capabilities. From the 2000s onward, Mars has become a popular destination. India's second planetary science mission (Mangalyaan or Mars Orbiter Mission) and the United Arab Emirates' first mission (Emirates Mars Mission Hope orbiter) are presently conducting orbital science at Mars. China conducted its first planetary mission outside of cis-lunar space in 2021, successfully performing Tianwen-1 orbital insertion and then successfully landing and exploring with the Zhurong rover on the Martian surface.

A growing number of national space agencies have expressed planetary science ambitions, such as South Korea, New Zealand, Mexico, Brazil, Saudi Arabia, and South Africa (Patel, 2019). Cooperation between the United States and these national agencies at Mars presents an opportunity to broaden the sphere of influence and leverage growing capacities of these nations toward shared goals at Mars. Partnership with other space agencies offers a means to "grow the pie" of activity at Mars (Figure 3.1). Regular missions to Mars will provide more opportunity for external partners than larger, less frequent missions. In particular, emerging space agencies will be able to mature their nation's spacefaring capabilities by increasing the scope of their partnership role on missions throughout the program.

Interest in such opportunities by international space agencies has already been demonstrated (e.g., Artemis Accords, 2020). A more concrete example of cooperation in practice is the Hope orbiter of the Emirates Mars Mission of the United Arab Emirates Space Agency, in which systems engineering of the spacecraft was shared by Mohammed bin Rashid Space Centre and the University of Colorado, and instruments were built via partnership with U.S. universities, demonstrating agency–academia–industry collaborations across borders.

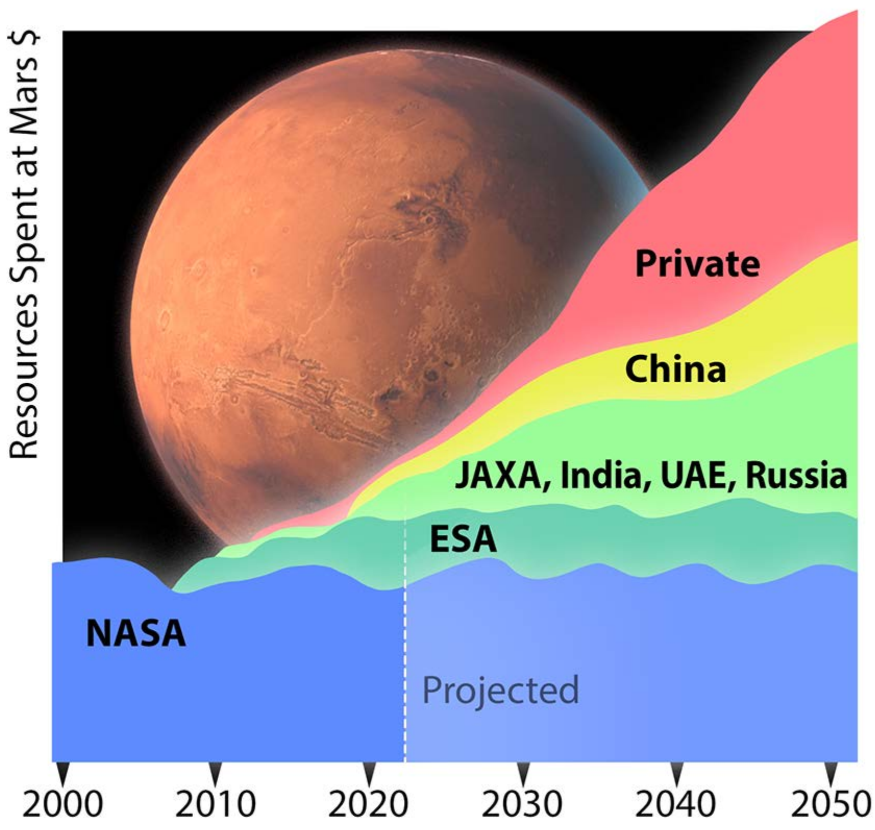


Figure 3.1: Qualitative depiction of the last decade has seen a growth in the diversity of stakeholders investing in Mars exploration. New stakeholders are expected to continue into the future as other national agencies and private ventures (e.g., SpaceX) grow investments, allowing NASA to leverage partnerships to achieve science and exploration goals.

3.3 Diversify Access to STEM Jobs and Grow the STEM Workforce via Exciting Missions

Among the most exciting activities in the space sector are planetary science missions, which carry a high public awareness. The positive influence of planetary exploration on the science, technology, engineering, and math (STEM) fields and current and future workforce occurs at all ages. Planetary scientists who analyze the data are a relatively small proportion of those who benefit from Mars exploration. Space missions excite children in schools to learn about STEM fields. University student internships in space and planetary science train the next generation of the STEM workforce. In industry, planetary mission projects are one means of workforce recruitment and retention. The opportunity to work on regular, challenging, exciting missions would provide industry opportunities to recruit, develop, and retain a diverse workforce. Increased numbers of Mars missions—and indeed all planetary exploration missions—can broaden the workforce and diversify the type and number of institutions associated with aerospace endeavors.

A program of Mars exploration that capitalizes on partnerships, including with universities, would have many benefits for opening new, exciting pathways to STEM careers and facilitating retention of undergraduate students in STEM. With science operations for the Perseverance and Curiosity rovers as well as select orbital instruments (e.g., HiRISE, Hope instruments) already being conducted in large part from college campuses, a next step is for mission operations, or significant fractions of them, to leverage the skilled early career workforce and natural advantages of universities in training a larger and more diverse STEM workforce. Operations with student workforces also realize cost savings relative to teams of solely professionals. Mars surface missions' high cadence frequency of operations activity (daily or every few days) works well for student staffing and engagement. It is a natural evolution for Mars exploration to design competitions for science payloads and science missions to encourage U.S. university teams or teams of industry-university or NASA-university partners.

NASA has an opportunity to maintain national leadership in diverse and productive science by increasing the funding opportunities for early career cohorts of engineers and scientists who might otherwise be attracted elsewhere. As young cohorts are proportionally more balanced in gender and racial demographics than the upper levels within the field (Pico et al., 2020; Riegle-Crumb et al., 2019), such is a means of also diversifying professional STEM workforce demographics via greater participation in this exciting national endeavor. As diverse teams out-perform non-diverse teams (Hong and Page, 2004; Nielsen et al., 2018, 2017), decreasing the barrier to entry for parties currently underrepresented in space science is a goal that will have many positive externalities for the field, both in science, engineering, industry, and geopolitics. The proximity of Mars and relative maturity of mission design allows missions to Mars to intentionally serve as training grounds for the next generation of STEM professionals.

4. Key Elements of the Landed Mars Exploration Strategy

Technology alone cannot revolutionize access to the Mars surface, particularly in a manner that makes per mission cost more affordable (Section 2). Instead, technical innovation must go hand-in-hand with multi-pronged strategic elements that increase the cadence of builds, lower per-mission cost, and thereby allow technically bold approaches where some risks to individual missions are accepted (Wertz et al., 2011; Appendix A.5). A driving attribute of the Frequent, Affordable, Bold (FAB) strategy (Figure 4.1) is completing more Mars activities at significantly lower per-unit costs than traditional NASA Mars missions.

4.1 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 (Wertz et al., 2011). While lower mission frequencies lead to risk-adverse postures that can drive higher costs, the "space spiral" can be reversed so that higher cadences allow more tolerant approaches thereby lowering costs (Figure 4.2; see Appendix A.5 for further discussion). In an environment where resources are limited and missions to other destinations continue to grow, a program of Mars exploration that strives for high frequency must also be driven to lower costs and more limited average per-mission scope (Bearden, 2003). Higher frequency missions will lead to more experienced teams, large amounts of flight-proven hardware and technologies, higher risk tolerance, and overall reduction of cost as the program moves up the "learning curve" (Chen and McLennan, 2004). By building multiple copies of a spacecraft, large cost reductions can occur even in the first few iterations as non-recurring costs from the first mission can be leveraged in subsequent iterations (Figure 4.3). This provides benefits across the planetary

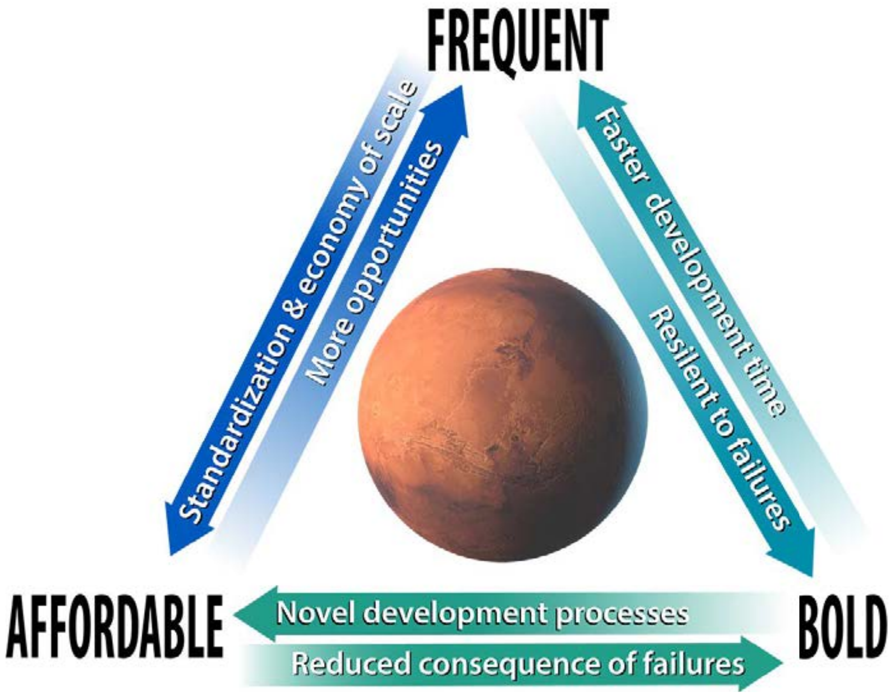


Figure 4.1: Elements of the Frequent, Affordable, Bold strategy.

exploration portfolio as mission cost reduction can flow first from the CLPS program to Mars and then outwards towards other targets of planetary exploration.

NASA missions have experienced enormous cost growth, at least partly driven by the risk profile adopted by its "flagship" missions, and big cost savings have been observed by shifting missions into higher "risk categories" where paperwork, testing, and reviews are less stringent (Hong and Page, 2004; Shao et al., 2013).

Figure 4.2: (a) The "space spiral" concept illustrates how long schedules and few missions can drive demand for very high reliability and higher costs. (b) By contrast, shorter schedules and more missions lower the reliability pressure on each, in turn, lowering cost per mission. Judicious programmatic planning can foster the favorable "space spiral."

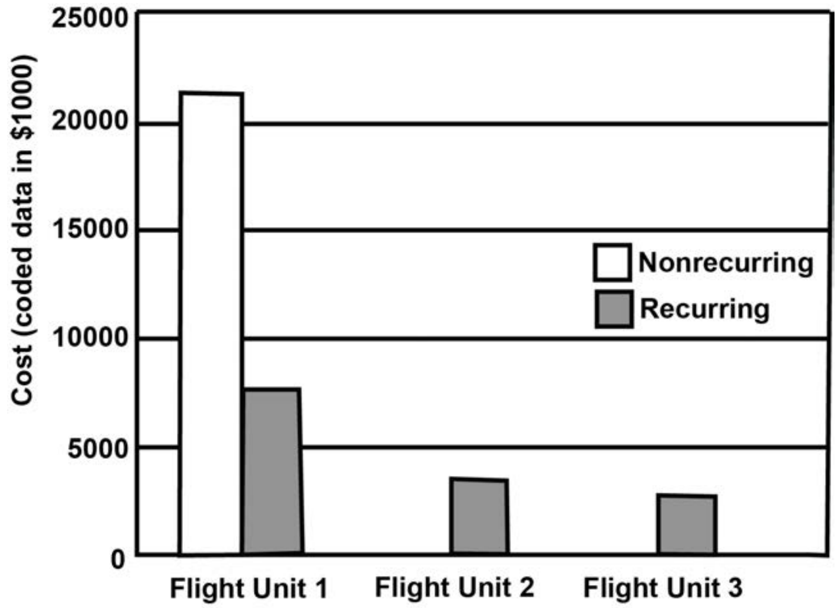


Figure 4.3: Per-unit cost drops with multiple flight copies. Analysis of expenditures for the ST-5 mission from the New Millennium program for satellite constellations. First flight unit costs include non-recurring costs, which are approximately 60% of the total (Chen and McLennan, 2004). Substantial cost savings can be achieved in the first few copies of a spacecraft manufacture, even without investments in assembly line manufacturing.

A program centered around "frequent" missions begins to be inoculated against the risk inherent in the program as the existence of multiple iterations cements the attitude that occasional failures can be tolerated and will in fact lead to improvements for subsequent missions (see Section 4.3). This in turn allows development to proceed faster and for bolder approaches to be contemplated. Additionally, this approach can rapidly accrue an experienced workforce and a supply of flight proven hardware and approaches. Bringing down costs of workforce, design, manufacturing, and testing can rapidly decrease the overall cost of a mission and a program allowing for the continuation of a rapid cadence of missions.

Realizing the benefits of frequent missions requires a steady long-term commitment. Missions need to occur with enough frequency to encourage investment and enable companies to invest in necessary infrastructure. The Commercial Lunar Payload Services (CLPS) project has developed a two-missions-per-year cadence in consultation with the commercial community. Industry experts suggest the twice per year flight rate is high enough to warrant both industry investment and to sustain more than one commercial entity. A similar cadence for Mars missions, centered on Mars launch windows rather than years may provide similar benefits. A commitment of at least 2 launches per opportunity over 10 years will provide the necessary frequency to substantially reduce costs and provide substantial science return. This will break the negative "space spiral" phenomenon (Wertz et al., 2011; Figure 4.3) in which longer schedules and fewer missions lead to greater demands for higher reliability and to higher cost. The two launches can include multiple lower-cost spacecraft and could provide many opportunities for participation from private, commercial, and international partners. Flying at each Mars mission opportunity, following an approximately 26-month cadence, will avoid long gaps between missions, which can lead to loss of focus and skills and decreased risk tolerance. This recurring cadence will help demonstrate on-going progress for the public and other stakeholders in order to maintain and increase program support. The results achieved across this string of missions would lead to a substantial increase in new opportunities for science discovery, the cadence of hypothesis development and test, and the quality of data from diverse parts of the Mars system.

The quantity and diversity of potential landing sites on Mars required to deliver groundbreaking science cannot be addressed by only one or two large complex missions (Section 1.1; Appendix A.2). A broad-based exploration of the planet that utilizes the full variety of science mission types will be the most successful and efficient means for exploring the planet. While missions like Mars sample return have the potential to deliver incredible science return, placing those discoveries within appropriate context will multiply the benefits. Frequent missions would increase the number of surface payload opportunities to expand our knowledge of Mars.

4.2 Affordable: Mostly Low-cost; Occasional Larger Missions

Over the history of Mars surface exploration, critical results have arisen from a variety of mission styles. These range from directed high-profile and high-budget missions, such as the Viking 1 and 2 missions in the 1970s ($6.2B for two landers and two orbiters, all costs in FY22$; Phases A–D) and the Curiosity ($2.8B) and Perseverance ($2.4B) rovers in the past decade to the PI-led Mars Exploration Rovers ($1.0B for 2 rovers), the mid-range Mars Scout and Discovery missions like Phoenix ($441M) and InSight ($683M) all the way down to the "faster, better, cheaper" Mars Pathfinder mission in the 90s ($371M) (Table 2.2). Currently, the planetary science community has placed a significant focus on the series of directed missions between NASA and ESA making up the ambitious plan to return samples from Mars currently being collected by the Perseverance rover.

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. These include the soil composition measurements of Pathfinder (e.g., Bell et al., 2000), direct observation of near-surface water ice from Phoenix (Smith et al., 2009), discovery and *in situ* exploration of two distinctive types of ancient habitable environments with the MERs (Squyres et al., 2004, 2008), and the size of the Martian core from InSight (Stähler et al., 2021), among many others. Ground-breaking results are certainly expected from Mars Sample Return over the next several years; however, the pace, diversity, and significance of science results from Mars also critically depends on data from surface missions focused on other science areas of interest that provide critical data pieces for understanding Mars as an evolving system of comparable complexity to Earth (Section 1.1).

Frequency requires affordability, and affordability is realized by processes that generate components and subsystems with enough frequency to reduce non-recurring engineering (Section 2.5). A component of NRE reduction is definition of a set of science mission types (Section 5.2) that set defined systems to which unique payload capabilities (with standardized interfaces) may be added so that each landed element is not bespoke. In turn, affordability enables a bolder approach that makes the program resilient to single mission failure, thereby allowing innovative approaches. A component of the affordability strategy is handling of risk (Section 4.3) and the engagement with a broader community of potential partners with roles where industries shares risk in providing Mars services (Section 5.4). Use of shared technologies across the space sector (e.g., qualifying commercial components) is also key for lowering per unit mission costs (Section 5.3). Such affordable, fast-paced missions can open up science opportunities for researchers and institutions outside of the limited number of mission-focused institutions presently capable of supporting large-directed missions; well-conceived partnerships can also be cost reducing. The diversity of people, institutions, and science enabled by affordable mission classes give the necessary breadth of Mars science to complement the depth of science available to large, directed missions.

A range of approaches for reducing costs (Chapter 5; Appendix A.5; A.6) are examined to help make these affordable missions a reality.

Box 3 Frequent, Affordable, Bold compared to Faster, Better, Cheaper

Frequent, Affordable, Bold (FAB) draws from but goes beyond Faster, Better, Cheaper (FBC) by emphasizing a sustained programmatic approach at the destination rather than putting the onus on single missions. FBC is widely maligned, but the first 10 missions actually had 90% success rate (Frank, 2019; see Appendix A.4 for further discussion). FBC emphasized short mission cycle, reduced mission cost, and higher science return per dollar. FAB emphasizes maintenance of a predictable high cadence of missions, low program cost by changing implementation partnership approaches, and bold execution, explicitly embracing a higher risk posture and new technologies that permit the affordable and frequent elements.

4.3 Bold: Accepting Risk Appropriate to Lower Cost; Shared Responsibility for Risk

One of the fundamental characteristics of the FAB strategy is the desire to be bold, i.e., aggressive when defining mission timelines, goals, capabilities, and budgets. Flying more frequently with a regular cadence allows a different balance on the risk/reward spectrum. 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. Encouraging all parties to seek higher return on investment, even when encumbered with additional risk, can lead to better science, more engaging missions, and more innovative solutions. Even if some risks are realized, having the next set of missions already in the pipeline, possibly with some potential to adapt based on recent failures, should facilitate a 'bold' approach towards FAB missions.

Early NASA solar system missions had rapid cadences and higher failure rates, but many successes. This approach allowed lowering development costs and leveraging simultaneous or near-simultaneous builds. A similar approach is being employed by SpaceX today in its rocket developments, in which failure and then eventual success are part of the process. NASA has moved away from this approach for planetary exploration—one of the drivers of per mission cost growth—but programs such as CRS and CLPS are opening the door to a more risk tolerant strategy within NASA. CRS has already demonstrated that commercial vendors can be allowed to fail when providing services to NASA without suffering the same consequences as a 'NASA failure.' It is still too early to demonstrate the success rate of CLPS missions, but NASA has publicly stated a willingness to accept failed commercial missions to enable lower cost and more frequent flights (Foust, 2021). Our FAB approach is distinct from Faster, Better, Cheaper (Box 3). Lessons learned during FBC include the importance of margins on mass, power, cost and/or schedule, small coordinated teams, and clear lines of communication to allow teams under tight constraints to have adequate resources of some nature at their disposal to mitigate risks as they are discovered (JPL Special Review Board, 2000).

Consequently, any discussion about being bold must also include understanding risk. Appendices A.4 and A.5 both address aspects of the relationship between cost, schedule and technical risk. As the cost and complexity of space missions has risen, the tolerance for mission failure has gone down. For a FAB strategy to be successful, it must incorporate a better understanding of how much risk is acceptable and who bears the risk. Importantly, stakeholders must clearly come to agreement on foolish versus acceptable risk and how to differentiate these for a project during development.

NASA has developed a fairly rigid, comprehensive approach towards both understanding and managing risk for government missions, with extensive documentation, many layers of review, and well defined accountability procedures for classes A–D and technology demonstration missions. While this approach has largely proven effective at reducing mission failure, it frequently engenders a high overhead to both manage the process and ensure that risks are properly mitigated. That high overhead is not consistent with the core premise of FAB. As a commercial space industry has emerged, commercial vendors have developed different approaches towards managing risk and assess the impact of mission risk in different ways.

Many of those commercial approaches may be more consistent with the intentions of FAB but for missions that include both NASA and industry partners, it's critical that the risk posture be defined early and bought into by all parties. For mission science principal investigators, this might include funding to simultaneously build a flight spare, which can be part of a reflight (in case of failure) or available for future missions (if the primary is successful).

In Sections 5.3 and 5.4, we argue that the commercial sector may be ready to contribute to Mars exploration via commercial service models. NASA's move towards commercialization and buying services rather than development support is one aspect of how NASA is attempting to shift key aspects of risk management to the commercial community. Firm fixed price contracts clearly push the heart of cost risk onto the commercial vendor community.

For the FAB strategy, it will be important to clearly define who is responsible for the various aspects of risk for each mission. Defining responsibility allows all parties to make sound choices about their level of engagement and investment and work together to implement a risk management approach that is consistent with each of their goals.

5. Path to Implementation

5.1 The Criticality of Long-term Strategic Thinking

As discussed in previous sections, revolutionizing surface access involves a positive feedback between reducing mission cost and increasing mission frequency. Achieving this requires a long-term strategic view of how cost reduction can be achieved over the course of the entire program, as well as how synergies can be exploited between programs (e.g., surface and orbital, Mars and lunar, and inner and outer solar system exploration) to achieve economies of scale and reduce non-recurring engineering.

The starting point for formulating this strategy is a long-term vision of science that must be performed on Mars surface (e.g., MASWG, 2020; Sections 1.1, A.1). Potential approaches to cost reduction are discussed in Sections 5.3–5.5 and Appendix 5 and draw from many sources, including past studies of this topic (Wertz et al., 2011), space technology-oriented white papers submitted to the Planetary Science and Astrobiology Decadal Survey (PSADS) (Barba et al., 2020; Edwards et al., 2021; Matthies et al., 2020), and related roadmaps that address a broader set of applications than planetary exploration. Breaking potential roadmap missions down will identify where standardization of major subsystems, components, and interfaces across programs and missions can lead to long-term cost savings from economies of scale. Finding commonalities between planetary science missions and terrestrial technology trends will identify where terrestrial technology might be leveraged and what investments are required to make that technology transfer viable (Section 5.3).

As the science objectives are identified, the strategy also needs to examine where investment in multiple builds of identical systems (both delivery systems and science instruments) can enable lower costs. This then allows a standardized set of science "mission types" (Section

5.2) to which instrument providers can orient their requirements and interfaces and to which landing system providers can design for multi-builds to reduce NRE. Some science objectives will require custom development, but even in those cases, identification of standard interfaces to common landers or mobility systems can lower mission costs. Multiple build strategies also change the risk discussion because hardware has already been stockpiled or is in development if failures occur.

Additional elements of the strategy include growing the set of stakeholders interested in the Mars surface (Section 5.4), enabling new partnerships (Section 5.5), and aligning robotic exploration strategy with human exploration (MEPAG Goal IV; Mars Exploration Program Analysis Group MEPAG, 2020). Finding forums for engaging this broader community of stakeholders and encouraging diverse inputs into future mission concepts are key to establishing the long term framework for frequent landed missions to Mars.

Mission Science Objective	**Small, hard fixed lander**	**Soft fixed lander**	**Aerial mobility**	**Rover mobility**	**Large (optionally mobile)**
Surface-atmosphere boundary layer interactions (incl. trace gas measurements)	✓	✓	✓	✓	✓
Geophysics (subsurface ice/water w/ resistivity, GPR, Seismo, magnetism)	✓	✓	✓	✓	✓
Polar Layer Deposit climate record determination		✓	✓	✓	✓
Mid-latitude ice sampling for characterization		✓		✓	✓
Geology Field Explorer for characterizing ancient habitable environments, environmental change			✓	✓	✓
Geochronology for Martian and solar system chronology				✓	✓

Table 5.1: Examples of mapping Science Goals to FAB Mission Capability Classes

5.2 Streamlining Science Implementation: Discrete Mission Types

Taking a FAB programmatic approach, orbital and surface missions are both desirable (see also Box 4). Our workshop focused on landed science and identified that the *in-situ* measurements required to address key Mars science questions (Section 1.1; Appendix A.1) can be accomplished via payloads carried on five general classes of missions with approximate payload masses (instruments + sampling/surface interaction tools) as shown in Table 5.1. Streamlining the number of mission types allows platform and interface standardization to realize cost reduction from multiple builds. These missions are:

- **Small, hard fixed lander ($\geq$ 5-kg science payload):** A lander with a reduced number of subsystems: passive, aeroshell-only entry system, no propulsion or parachute subsystems. It would use uncontrolled entry (no GNC), likely resulting in large landed footprints (~100 km downtrack). The payload(s) needs to be robust to high g-loads, on the order of 1000 g's and not require precise placement or orientation (e.g., Barba et al., 2019). This mission class is especially well-suited to atmospheric or certain geophysical (e.g., seismic) measurements, which have wide tolerances on landing precision requirements and often benefit from coordinated measurements taken by multiple assets in a network.

- **Soft fixed lander ($\geq$20-kg science and enabling payload):** A landing system perhaps similar to Phoenix and InSight. The landing is more accurate and allows for precise deployment, placement and orientation of the payload on the surface. This class is well suited to seismic and atmospheric measurements requiring more capable or sensitive payloads than can be accommodated on hard landers. Perhaps modest mobility (Pathfinder-like; $\lesssim$100 m) is permitted with a small accompanying mobile asset, allowing sample acquisition (fetch and retrieve), or modest surface interaction (arm; vacuum system).

- **Aerial mobile (~3–5-kg science payload), potential for different EDL systems:** The Ingenuity helicopter technology demonstration proved powered flight on Mars as well as the utility of airborne data collection, in this case imaging. Ingenuity weighed 1.8 kg total, had a commercial RGB camera as science payload, and was tethered to the Perseverance for comm (Balaram et al., 2018), but future standalone Mars aerial missions could carry 3–5 kg of payload and provide relay communications to orbit. This class of mobile mission would enable basic mapping, stratigraphy, coarse mineralogy, chemistry, over potentially 2–3 km traverse distances (Bapst et al., 2021). A potential future class of mission might be able to perform mid-air deployment, simplifying EDL system mass and cost (Delaune et al., 2020).

- **Medium mobile ($\geq$20-kg science and enabling payload):** This class of missions is well-suited for exploratory missions with capable, integrated suites for high resolution *in situ* observations (microimaging, mineralogy, chemistry, and isotopes). The payload mass includes enabling components such as arms and end effectuators for manipulation of surface materials. Instrument complexity can trade against distance, where the primary science targets range over a significant distance (>10 km) from the landing site and the landing site is precisely selected. This includes geologic investigations to understand past climates and habitable environments, shallow subsurface exploration, and possibly polar science.

- **Large mobile (≥100-kg science and enabling payload):** Science questions that drive the need for large mobile assets, such as *in situ* age dating or life detection will require EDL systems capable of precise delivery of large systems. Missions will carry capable instruments (e.g., mass spectrometers, biosignature detection suites for fluid analyses) and enabling systems (e.g., robot arms, drills, etc.) that potentially need to interact with the surface in more complex ways (e.g., >1m drilling or coring for sample collection) and traverse length requirements could trade off with sampling complexity.

Standardizing mission design and payload interfaces for each class of landers would enable a diversity of science instrument payloads without the need of a unique design for each of the five platforms. This contrasts to historical approaches where Mars landed assets have been uniquely tailored to accommodate payloads and landing sites.

Concomitant measurements from multiple landed assets enable geophysical and atmospheric investigations. Multiple sites with ice and rock records can be investigated to build information on the Mars system over space and time.

Collectively, these mission classes address all the major MEPAG science goals (Appendix A.1). As discussed in Section 5.1, a strategic roadmap is needed to maximize the science return of this program. Additionally, a list of priority landing sites that maps to science goals, and the characteristics of those landing sites (elevations, hazards, and required landing precision) must be maintained by the Mars community to foster common understanding (see Appendix A.2). Our workshop efforts defined initial mission types and landing site lists, but for a FAB program, such is a list that would be developed and maintained by the Mars program and/or MEPAG to involve stakeholders.

5.3 Shared Technology/Technology Investment with Larger Space Economy

Missions to the surface of Mars pose unique challenges that drive technology planning (Edwards et al., 2021; e.g., Section 2.3). At the same time, Mars missions share common functional capability needs with other elements of the larger space economy, as well as other rapidly evolving technology arenas, which offers a powerful approach to achieving greatly reduced mission cost (Figure 5.1). In support of this goal, Mars mission planners should, wherever possible, seek to leverage existing and emerging technology solutions from aerospace

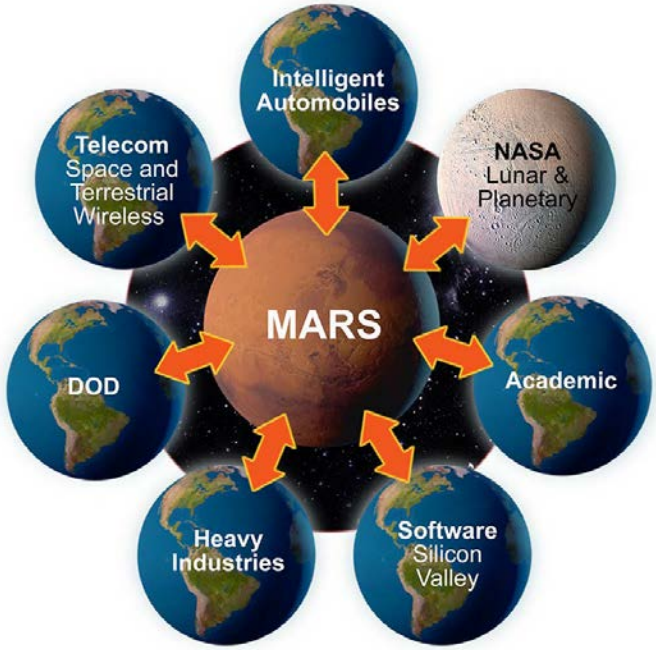


Figure 5.1: Mars pulls technology from—and can push technology to—other sectors. Future Mars missions can draw on technology developments from a wide range of sponsors and markets, enabling enhanced capabilities as well as reducing development and recurring costs.

and other sectors, including non-Mars planetary missions, Department of Defense investments, commercial space markets, automotive, telecommunication, and robotics terrestrial markets. Where new Mars capability needs are identified, efforts should be made to identify other potential non-Mars users with whom technology development costs can be shared. This offers the possibility of economies of scale, benefiting when far larger technology development investments are made on relevant technologies for other markets than is possible within only the Mars surface domain.

Many examples of shared technologies, applicable to Mars but driven by broader market needs, can be identified. We summarize a number of these here, while also pointing out areas where Mars poses unique challenges that may drive focused technology investments:

- *Mobility systems:* Physical mobility system design (actuators, wheel design) and autonomy (surface navigation, sensors, fault detection and recovery) are many common challenges faced by Mars, lunar, and terrestrial roving systems, with similar terrain and environmental requirements. Similar synergies exist for rotorcraft applications on Mars and Earth.

- *EDL:* While the thin atmosphere of Mars introduces many unique aspects to EDL, certain technologies can be leveraged across lunar, Mars, and other planetary applications. In particular, sensors for descent guidance (IMUs, radar, Doppler LiDAR), terrain-relative navigation (vision systems), and hazard avoidance (visual and LiDAR systems) can offer capabilities spanning diverse target needs (Carson et al., 2021).

- *CubeSat and SmallSat systems:* Thousands of CubeSat and SmallSat designs have been created and more than 1500 have flown in space. Many aspects of these systems are available as commercial, off-the-shelf capabilities readily available at comparatively low cost. Some of these components/systems may be applicable to use on Mars and represent a fast, cheap way to take advantage of an existing commercial market.

- *Rough landers:* DoD makes significant investments in impact attenuation systems for large airborne payload delivery, as well as very high g-load systems for smart munitions, including sensors and electronic packaging; both of these areas have high relevance for the design of low-cost hard landers and instruments for Mars.

- *Telecommunications:* Commercial Earth satellite and terrestrial telecommunication technologies offer a rich set of technologies that can be adapted to Mars needs. Existing Mars communication infrastructure may also be adaptable. In particular, NASA should seek to maximize synergies between lunar and Mars relay telecommunication architectures. Direct-to-Earth (DTE) links for Mars relay satellites will have much more challenging space losses than similar lunar relay satellites, driving the need for higher-power, higher-gain components on the relay orbiter DTE links. However, the proximity links between users and relay satellites share many characteristics, with common desire for high bandwidth, high connectivity, and low user burden (Reinhart et al., 2017).

- *Commercial electronics component technologies:* Rapid development of high-performance processors and sensors, driven by the automotive and cellphone industries, offers significant opportunities for large increases in capability with simultaneous dramatic reductions in mass, volume, power, and cost. As one example, the Ingenuity helicopter on the Mars 2020 mission very successfully leveraged a number of Commercial Off the Shelf (COTS) solutions, including a a commercial processor, commercial flight microcontrollers, Li-ion batteries, COTS cameras, and radio systems (Balaram et al., 2021).

- *Software Systems:* Rapid advances in autonomous navigation, artificial intelligence, and machine learning technologies can support a wide range of capabilities and behaviors needed by autonomous robotic explorers. The ability to robustly infuse open-source software from the research community can leverage significant external investments and speed mission development cycles. The incorporation of common flight software frameworks such as NASA's Core Flight System (cFS), or the adoption of similar terrestrial frameworks like ROS 2.0, can further increase reuse and minimize the development of common software capabilities (e.g., logging, file access, time-keeping).

By proactively tracking relevant emerging capabilities in the broad marketplace of space and terrestrial applications that can be rapidly adapted and applied to Mars mission needs, and by seeking non-Mars stakeholders with common capability needs with whom focused technology development partnerships can be established, future Mars missions can leverage increased capabilities and greatly reduced cost and schedule.

5.4 Growing the Pie: Revising Stakeholder Relationships to Increase the Market

Another tool for lowering cost and increasing frequency is to broaden and deepen the pool of participants in future Mars endeavors and create partner relationships that allow full activation of all stakeholders. A diverse community of stakeholders can bring additional funding to the table, reduce costs for development or operations, and/or identify revenue streams that reduce long-term expenditures (Figure 5.2).

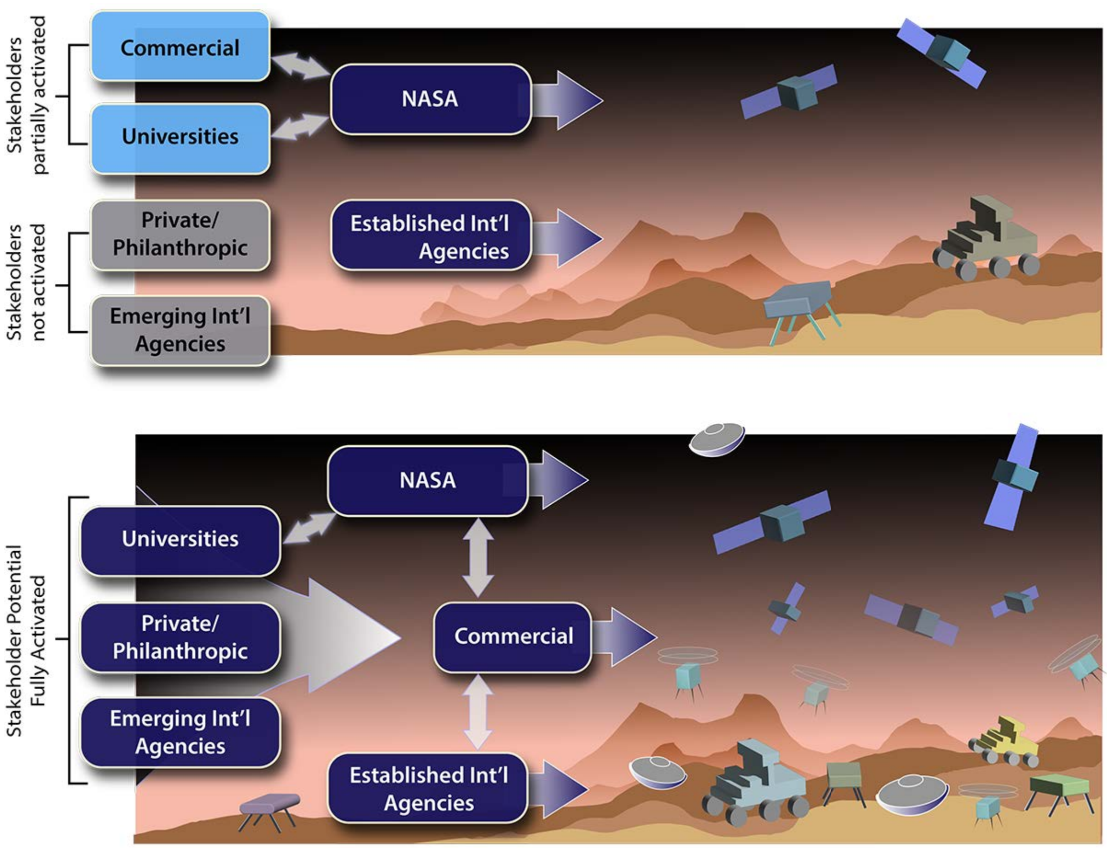


Figure 5.2: Changing partner relationships will grow the stakeholder pool that is investing at Mars.

Presently, the NASA and other established agencies (e.g., ESA, CNSA) provide the sole means of access to the Mars surface. Each of these engages, mostly via contracts, with commercial industry and universities to develop and deliver exploration systems. However, there is more capacity to conduct Mars exploration in these stakeholders than is presently activated, as both have private or internal funding streams for internal priorities. Additionally, presently emerging space agencies or private organizations with objectives at Mars have no surface access capabilities (Figure 5.2(a)).

The FAB strategy would provide an open framework for encouraging and enabling broader commercial participation in Mars-related activities that includes changing the nature of stakeholder relationships in ways that enable return on investment and facilitate commercial needs (Figure 5.2(b)). Some missions would remain directed and operated by NASA and other established agencies. Other missions would be conducted under a services model with commercial providers. Government commitment to a sustained program of frequent missions to Mars sets the floor for potential return on investment while creating opportunity and demand for multiple commercial entities by enabling engagement with both present agency customers as well as new entrants that bring additional capital and opportunities.

The initiation of a services model was also recommended in the MASWG 2020 report, which encouraged consideration of Commercial Cargo or CLPS models that fundamentally change the government role and provide potential models for how future commercial-government alliances for Mars might be built (see also Section 5.5). Finding similar opportunities to re-envision the relationship between traditional government sponsored space activities, academia, and private entities is also needed for FAB.

Scientific advancement is a key objective of the FAB strategy. While the science community and national agencies are obvious supporters, it will be important to demonstrate value in multiple scientific domains to engage broad support. Existing communities such as the Mars Exploration Planning Advisory Group (MEPAG) and the Decadal survey teams provide context for defining relative importance of specific science activities on Mars (Mars Exploration Program Analysis Group MEPAG, 2020; Planetary Science and Astrobiology Decadal Survey 2023–2032, 2021). Not all of the identified activities will lend themselves the implementation approach of FAB, but it will be important to document where there is alignment (see Sections 1.1, 5.2, and A.1).

An obvious stakeholder for the next decades is human exploration of Mars. FAB activities can reduce both technical and programmatic risk for human missions by testing key technical systems, demonstrating critical capabilities at Mars, doing site survey and analysis prior to human arrival, and discovering resources of value to human activities. Overlapping areas of need with traditional science needs include telecom, weather monitoring, and investigation of ice and hydrous minerals as *in situ* resources. The establishment of core infrastructure, such as communication relays, via FAB robotic surface mission support activities also supports future human missions, ultimately lowering cost and risk for those missions.

Beyond the science and NASA human exploration communities, there are a wide variety of potential stakeholders in FAB mission activities. A large portion of the existing aerospace community (both "New Space" and "Old Space") are potential participants. Some will participate to enhance their reputation, some will participate because they want to expand human presence beyond Earth, some will participate to demonstrate new technologies, some will participate purely for profit potential. Their contributions will likely take many forms, from technology contributions to joint mission opportunities to traditional government contractor roles. Multiple entities have expressed interest in missions to Mars, even absent government sponsorship. While there is little expectation for a stand-alone Mars economy today, the capital and interest from the commercial space and entertainment sectors can lead to opportunities. One example is entertainment where virtual competitions or participation in immersive experiences in a Martian landscape could take place, enabled by telecom bandwidth, and with commercial upside similar to other large budget entertainment endeavors (~$200–300M for films). Another example is philanthropic investment. As costs are lowered, mission execution enters the realm of what consortia of universities or private philanthropic organizations can undertake for scientific advancement. For comparison, academic-private-government consortia for ground-based observatories routinely raise $1B, and the Twinkle private space telescope mission is building a consortium of university users, using financing strategies that include folding insurance into the cost to mitigate participant risk. Finally, crowdsourcing has been successfully used for Earth Orbit missions (e.g., the Planetary Society's Lightsail-2; Vaughn and Friedman, 2021) and could play a partner role in funding Mars surface missions and their payloads. The key is organizing relationships so that stakeholders contribute to their full interest and potential.

Participation from international partners will also grow the stakeholder community. There is already a well-established practice of joint science missions across international agencies that should continue under FAB. The opportunity to contribute to Mars missions can be a significant motivator for developing space nations to increase skills and capability as discussed in Section 3.2, providing STEM opportunities that benefit those nations long term. Small agency customers, perhaps operating independently, will also grow the base of potential Mars services customers.

Each of these stakeholder communities brings a different perspective on what priority to assign to Mars activities, may have different definitions of return on investment, and may differ on desired pace for completing activities. It will be important to have considered many viewpoints in the development of the implementation plan and to capitalize on areas of shared interest. Each alignment represents an opportunity to broaden the stakeholder community. As specific mission plans are developed, attention should be paid to how early opportunities may buy down risk for future Mars missions. There will also be opportunities to demonstrate or advance capabilities that can be used for planetary science at destinations other than Mars. This will continue to build the stakeholder community.

Last, by providing a more frequent, regular cadence of activities at Mars, FAB should allow broader public engagement and excitement around space in general. STEM growth in the US can be directly traced to space accomplishments (Roush, 2019) and public interest in space missions results in both stronger government support and more commercial opportunity.

5.5 Incentivizing Partnerships with the Commercial Space Sector

In order to attract partners that can help achieve lower mission costs, the FAB program must provide benefits aligned with the interests of each potential partner. These benefits, outlined and described in Table 5.2, must be considered and factored into any new program.

Commercial space companies are a particularly important partner to attract, as they will serve as hardware implementers both for NASA and for their own purposes, including serving a broader set of customers and markets (Figure 5.2). Since they will incur much of the mission cost, it is important to incentivize low-cost implementation. We identified several strategies that create alignment between NASA and commercial partners and facilitate positive working relationships during the contracting phase:

- **Seek industry input early.** Government and industry are too often siloed from each other. Soliciting input on industry capabilities prior to drafting RFIs or other formal information-seeking documents is critical. Early information from industry via workshops, industry briefings, white papers, conference/symposia, etc. will allow NASA to evaluate the gap between NASA's objectives and industry's capabilities. The ultimate goals is to create programs that enable mutually beneficial outcomes while allowing effective industry investment and participation.

- **Clear requirements.** NASA must define a stable set of mission objectives to industry from the onset of the problem: an initial development phase can allow NASA and industry partners to refine these into a clear set of requirements for subsequent execution. This may take as long as a year of effort on NASA's part but saves money and time over the course of the program. Once established, changing requirements can result in system design changes and are a source of non-recurring engineering that should be avoided to keep partner costs low and the project on schedule. Requirements may vary by mission type and can be strategically planned with initial requirements in line with near-term capabilities, accompanied by clear signaling on time horizon for longer-term, more complex capability needs.

Benefit	Description	Type of Partner
Revenue	Revenue generation is required for organizations to continue operating.	Companies, non-profits
Branding/Image	The idea of being associated with Mars exploration is exciting to all relevant parties.	Companies, entertainment academia, emerging space agencies
Talent Attraction/Retention	A high-profile project related to Mars will attract new talent and provide high-quality work for existing staff.	Companies, academia, government agencies
Altruism	Science and exploration are generally perceived to be admirable goals.	Philanthropists, academia, well-funded space companies
National Prestige	The ability to put hardware into space is seen as a sign of a nation's technical prowess and therefore a sense of national pride.	Governments, Congress, White House, emerging space agencies
Risk Reduction / Planning for Human Exploration	Information about the Martian environment that better constrains the design parameters in which human space systems must operate will buy down risk for future Martian astronauts.	Government agencies, companies
Scientific Return	New data and observations addressing space agency science goals, and resulting in peer-reviewed papers which drive scientists' careers and attract interest from the general public.	Scientists, media, academi general public, space agencies
Workforce Training / Planning for Human Exploration	Educational institutions that teach the next generation of aerospace workers.	Academia, government agencies
Grants	Parties outside of for-profit institutions typically rely on external funding to support their research and/or operations.	Academia, non-profits
Jobs	Programs that benefit national economies through new jobs are important for political buy-in.	Congress, White House, space agencies
Enhanced Industrial Competition	Programs that transfer NASA knowledge to start-up companies through streamlined acquisition processes.	Emerging companies, experts from technical fielc outside traditional NASA base

Table 5.2: Benefits that can attract different types of partners. Note that an entity can fall into more than one partner type.

- **Avoid NASA's mission risk classification system.** NASA missions currently use well-defined risk classification systems (NASA, 2011) that, while effective, are expensive to implement and require considerable overhead to manage. To catalyze non-traditional participation, steer away from established heritage processes and nomenclature. Instead, define a risk approach that considers the needs of all partners. NASA and the partners must work together to define an approach to risk that allows commercial partners to manage risk within acceptable limits without imposing onerous processes.

- **Structure contracts to reflect the gap between NASA's need and commercial capability.** NASA has a variety of contract vehicles that offer different strengths and weaknesses. A phased approach can help NASA foster capabilities early in the program, and then transition to more of a services-based approach once those capabilities have been established. Space Act agreements can also facilitate growth of capabilities.

The overarching goal of these strategies is to keep costs low through clear communication between NASA and partners.

NASA has demonstrated a number of successful models on how to encourage the development of new commercial capabilities and then leveraging those capabilities to meet NASA's mission needs in a new and more affordable fashion. For example, as part of the Commercial Orbital Transportation Services (COTS) program, NASA supported a number of industry partners in developing and demonstrating capabilities to deliver and return cargo from the International Space Station (ISS). NASA engaged with a number of partners, providing technical and financial support, while partners completed a number of defined milestones leading towards initial demonstration missions to the ISS. The clear demand signal provided by the recurring need for ISS transportation services helped commercial providers secure investment needed to complete these demonstrations on a fixed price basis.

The COTS program served as the basis for NASA establishing the Commercial Resupply Services (CRS) program, which selected multiple providers to meet ISS cargo transportation requirements following the retirement of the Space Shuttle. The key enabler for commercial participation was the NASA-guaranteed purchase of 20MT of cargo to the ISS, which allowed a high-confidence business case to close for the proposing companies. Since its creation, the CRS program has flown nearly 40 flights to the ISS, and also served as a foundation for the Commercial Crew Program, which is now providing operational crew transport to and from the ISS.

NASA has also leveraged no-exchange-of-funds agreements in a number of areas to help new commercial partners infuse existing NASA capabilities as well as develop new capabilities that can be of benefit to new NASA missions. NASA's Lunar CATALYST program provided technical support for three companies developing commercial lunar landers, which in turn helped them compete in the CLPS services program. For planetary missions, the Lunar

Prospector development ($63M RY or $114M FY22) successfully achieved high science return at low cost by working to help industry (Hubbard et al., 1997). NASA SIMPLEx missions are now pursuing similar partnerings to accomplish science at the Moon, asteroids, and Mars at low cost.

With these lessons from successful NASA programs, we have identified three implementation principles for a frequent, affordable, bold Mars program that involves commercial partnerships:

1. Allow flexible contracting approaches that enable commercial partners to develop system capabilities which allow NASA to make meaningful scientific progress, while also supporting a broader range of potential users for such a system.

2. Provide technical as well as financial support, to allow emerging providers to draw on NASA's extensive expertise to help field new capabilities and reduce risk throughout program execution.

3. Establish and maintain clear demand to indicate NASA's interest in ongoing frequent missions to Mars in order to help encourage commercial investment in supporting these activities.

Box 4 provides additional potential programmatic next steps for the FAB portion of the Mars Exploration Program. Together, these principles provide a framework for how to construct a program that enables frequent, affordable, and bold missions to Mars.

Box 4 Near-term programmatic steps for the Agency

The FAB missions would be a subset of a larger Mars Exploration Program involving extended missions, technology development, and occasional large directed missions. FAB serves to increase the cadence of science discovery at Mars and continue sustained U.S. leadership, particularly of surface exploration, after sample return. This report does not attempt to provide a full prescriptive program of how to implement FAB. However, we suggest early steps that could lay the groundwork for early success.

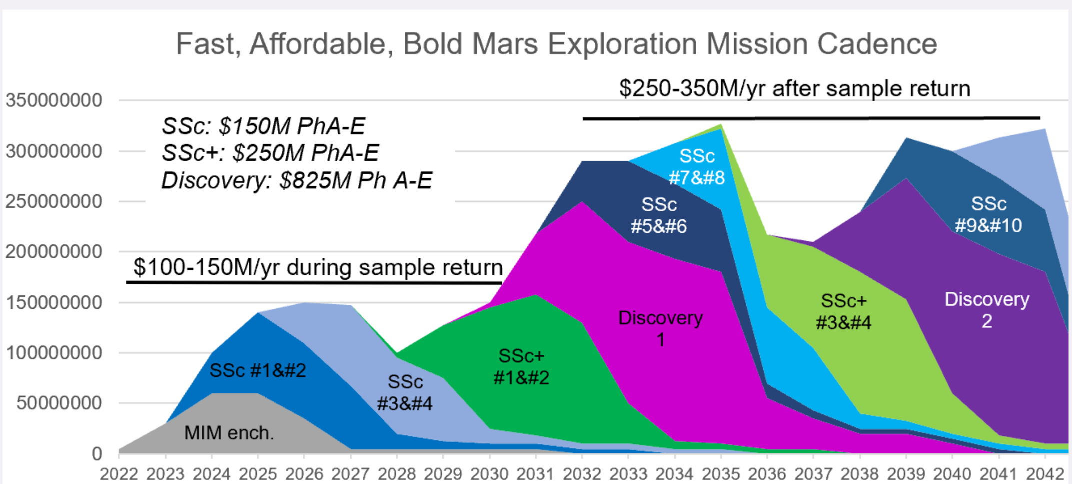
1. Identify where early mission activities might align with commercial interests while also supporting the longer term goals of FAB. Extending the current government communications infrastructure at Mars with commercial communication services might be a good starting point for discussion. Coupling early communications capabilities with orbital science opportunities will expand the partnership community and create a broader base of support.

2. Start a process to identify the types of technical capabilities that might be readily available for near-term Mars surface missions and those that might be available in the mid-term with modest investment. Information from existing commercial space companies about systems or capabilities that can put payloads on the surface of Mars are of particular interest. Workshops, conferences, NASA requests for information (RFI), and informal meetings with interested science and commercial communities are all valid approaches for gathering data. Aligning early mission plans with capabilities that are already or will soon be available can significantly lower cost. A notional cadence might be
   - Unguided hard landers
   - Soft, guided landers
   - Soft guided landers with mobility and steadily increasing mass
3. Work with entities such as MEPAG to develop a long-term science roadmap including a list of landing sites for a range of early mission opportunities covering multiple mission types (rough lander, soft landers, mobility systems of different sizes.)
   - Define the relevant science at each site and the enveloping reference investigations (nature of mobility and interaction with surface materials), identify any needed instrument development activities (hardened sensors for use with rough landers).
4. Start an instrument development track. A separate track of instrument development should be used to decouple instrumentation development from landing systems and develop science instrumentation compatible with higher-risk landers that may subject payloads to harsh environments (e.g., 2000g hard landing). Funding should be provided at a consistent and stable level. This encourages development of common payload requirements (reducing cost, improving flexibility, and simplifying payload accommodation for lander providers) and separates payloads from individual missions to facilitate instrument re-flight should a lander fail.
5. Fund a number of short term study/analysis activities with commercial companies to more deeply assess feasibility of the commercial concept and relevance to program needs, including consulting technical support from NASA. Joint partnerships like the CATALYST program that utilize tools such as Space Act Agreements may also be valuable. One of the studies should analyze acceptable risk levels across the community and define the right balance of risk to take while achieving all parties objectives.

6. Create agreements (contracts, grants, Space Act Agreements, cooperative agreements, etc.) for partnering with one or more entities to develop, deliver, or provide services for FAB activities. These agreements should provide opportunity for co-operative work between NASA and the entity. The agreements should also define development and performance milestones that will enable the frequent activities at Mars that FAB is championing.

7. Mars Missions Program Plan: develop a mainline program plan for at least 2 missions per opportunity, most oriented toward surface investigations. We envision missions starting from a "minimum viable product," e.g., small hard landers and communications satellites, and evolving the desired capabilities in this new risk environment. Investments in commercial technology to "close the gap" will enable mobility, soft landing, and higher mass after several years. The FAB-style missions will have interspersed traditional flagship and New Frontiers-like class missions under traditional agency approaches, if the science requirements warrant such approaches. The intent is not to supplant higher class missions within the Mars Exploration Program. These are important. Rather, FAB complements and extends the science by small spacecraft to Discovery type competitions under the FAB model.

An annual budget of \$100–\$150M/yr during sample return and \$250–\$350M/yr thereafter (in line with the CLPS Lunar plan) would support a robust suite of competed, FAB style missions of increasing capability and scope. These are envisioned as a component of a broader Mars Exploration Program that includes strategic missions, technology development, and extended missions (~\$500–\$600M level). For FAB programmatic success, funding must be consistent and committed over a set number of years (~8–10 yrs) and renewable beyond that time frame, based on overall program performance.



Proposed sample program provides 8–10 missions each decade with 2 more in development.

Even accepting additional risk on a per-mission basis, the overall probability of program success remains high.

Our report focused on how to revolutionize access to the surface. The FAB approach naturally could also encompass orbiting missions. Provision of communication infrastructure at Mars is essential for FAB landed missions. In addition to small landers, FAB missions pairing commercial communication services with science payload could be an early desirable type of FAB mission. Incorporation of cross-directorate, international, and private partners in FAB missions is also desirable.

A progression of missions conducted under a services model could revolutionize access to the Martian surface.

Appendices

A.1 Mission Classes Suited to Addressing Mars Exploration Program Analysis Group (MEPAG) Goals

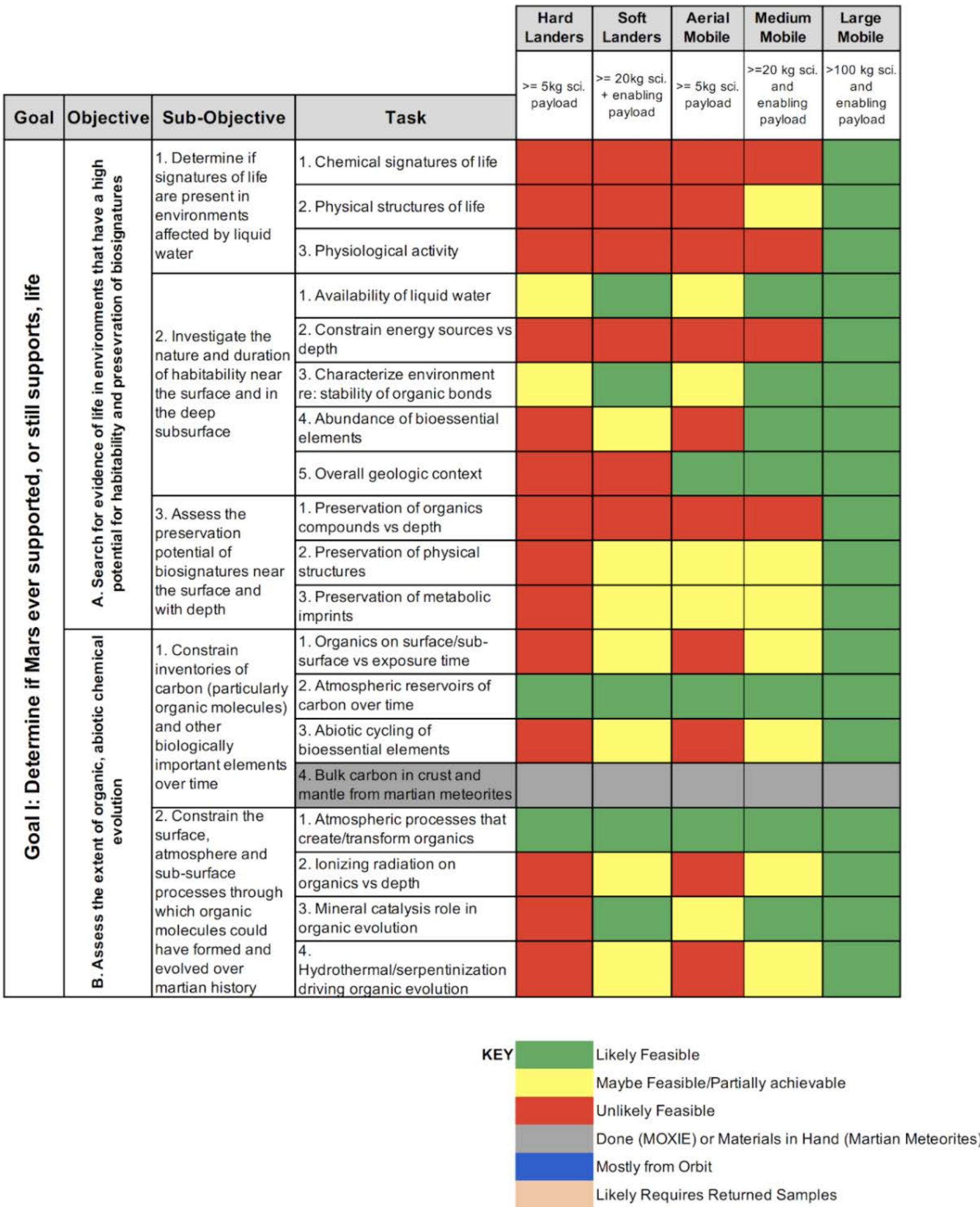
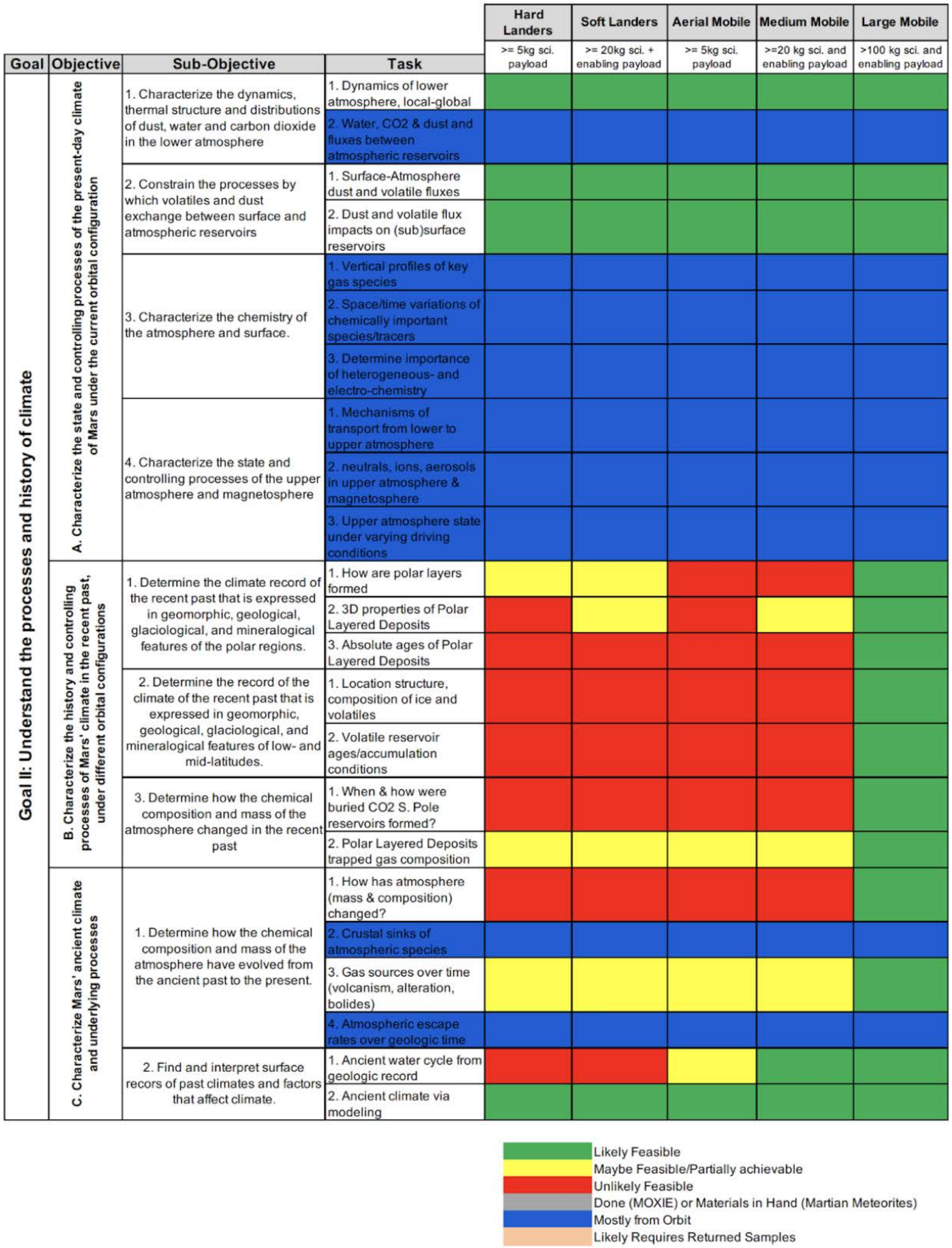


Figure A.1: Goal I (Life)



Goal	Objective	Sub-Objective	Task	Hard Landers (>= 5kg sci. payload)	Soft Landers (>= 20kg sci. + enabling payload)	Aerial Mobile (>= 5kg sci. payload)	Medium Mobile (>=20 kg sci. and enabling payload)	Large Mobile (>100 kg sci. and enabling payload)
Goal II: Understand the processes and history of climate	A. Characterize the state and controlling processes of the present-day climate of Mars under the current orbital configuration	1. Characterize the dynamics, thermal structure and distributions of dust, water and carbon dioxide in the lower atmosphere	1. Dynamics of lower atmosphere, local-global	Green	Green	Green	Green	Green
			2. Water, CO2 & dust and fluxes between atmospheric reservoirs	Blue	Blue	Blue	Blue	Blue
		2. Constrain the processes by which volatiles and dust exchange between surface and atmospheric reservoirs	1. Surface-Atmosphere dust and volatile fluxes	Green	Green	Green	Green	Green
			2. Dust and volatile flux impacts on (sub)surface reservoirs	Green	Green	Green	Green	Green
		3. Characterize the chemistry of the atmosphere and surface.	1. Vertical profiles of key gas species	Blue	Blue	Blue	Blue	Blue
			2. Space/time variations of chemically important species/tracers	Blue	Blue	Blue	Blue	Blue
			3. Determine importance of heterogeneous- and electro-chemistry	Blue	Blue	Blue	Blue	Blue
		4. Characterize the state and controlling processes of the upper atmosphere and magnetosphere	1. Mechanisms of transport from lower to upper atmosphere	Blue	Blue	Blue	Blue	Blue
			2. neutrals, ions, aerosols in upper atmosphere & magnetosphere	Blue	Blue	Blue	Blue	Blue
			3. Upper atmosphere state under varying driving conditions	Blue	Blue	Blue	Blue	Blue
	B. Characterize the history and controlling processes of Mars' climate in the recent past, under different orbital configurations	1. Determine the climate record of the recent past that is expressed in geomorphic, geological, glaciological, and mineralogical features of the polar regions.	1. How are polar layers formed	Yellow	Yellow	Red	Red	Green
			2. 3D properties of Polar Layered Deposits	Red	Yellow	Red	Yellow	Green
			3. Absolute ages of Polar Layered Deposits	Red	Red	Red	Red	Green
		2. Determine the record of the climate of the recent past that is expressed in geomorphic, geological, glaciological, and mineralogical features of low- and mid-latitudes.	1. Location structure, composition of ice and volatiles	Red	Red	Red	Red	Green
			2. Volatile reservoir ages/accumulation conditions	Red	Red	Red	Red	Green
		3. Determine how the chemical composition and mass of the atmosphere changed in the recent past	1. When & how were buried CO2 S. Pole reservoirs formed?	Red	Red	Red	Red	Green
			2. Polar Layered Deposits trapped gas composition	Yellow	Yellow	Yellow	Yellow	Green
	C. Characterize Mars' ancient climate and underlying processes	1. Determine how the chemical composition and mass of the atmosphere have evolved from the ancient past to the present.	1. How has atmosphere (mass & composition) changed?	Red	Red	Red	Red	Green
			2. Crustal sinks of atmospheric species	Blue	Blue	Blue	Blue	Blue
			3. Gas sources over time (volcanism, alteration, bolides)	Yellow	Yellow	Yellow	Yellow	Green
			4. Atmospheric escape rates over geologic time	Blue	Blue	Blue	Blue	Blue
		2. Find and interpret surface recors of past climates and factors that affect climate.	1. Ancient water cycle from geologic record	Red	Red	Yellow	Green	Green
			2. Ancient climate via modeling	Green	Green	Green	Green	Green

Green	Likely Feasible
Yellow	Maybe Feasible/Partially achievable
Red	Unlikely Feasible
Grey	Done (MOXIE) or Materials in Hand (Martian Meteorites)
Blue	Mostly from Orbit
Peach	Likely Requires Returned Samples

Figure A.2: Goal II (Climate)

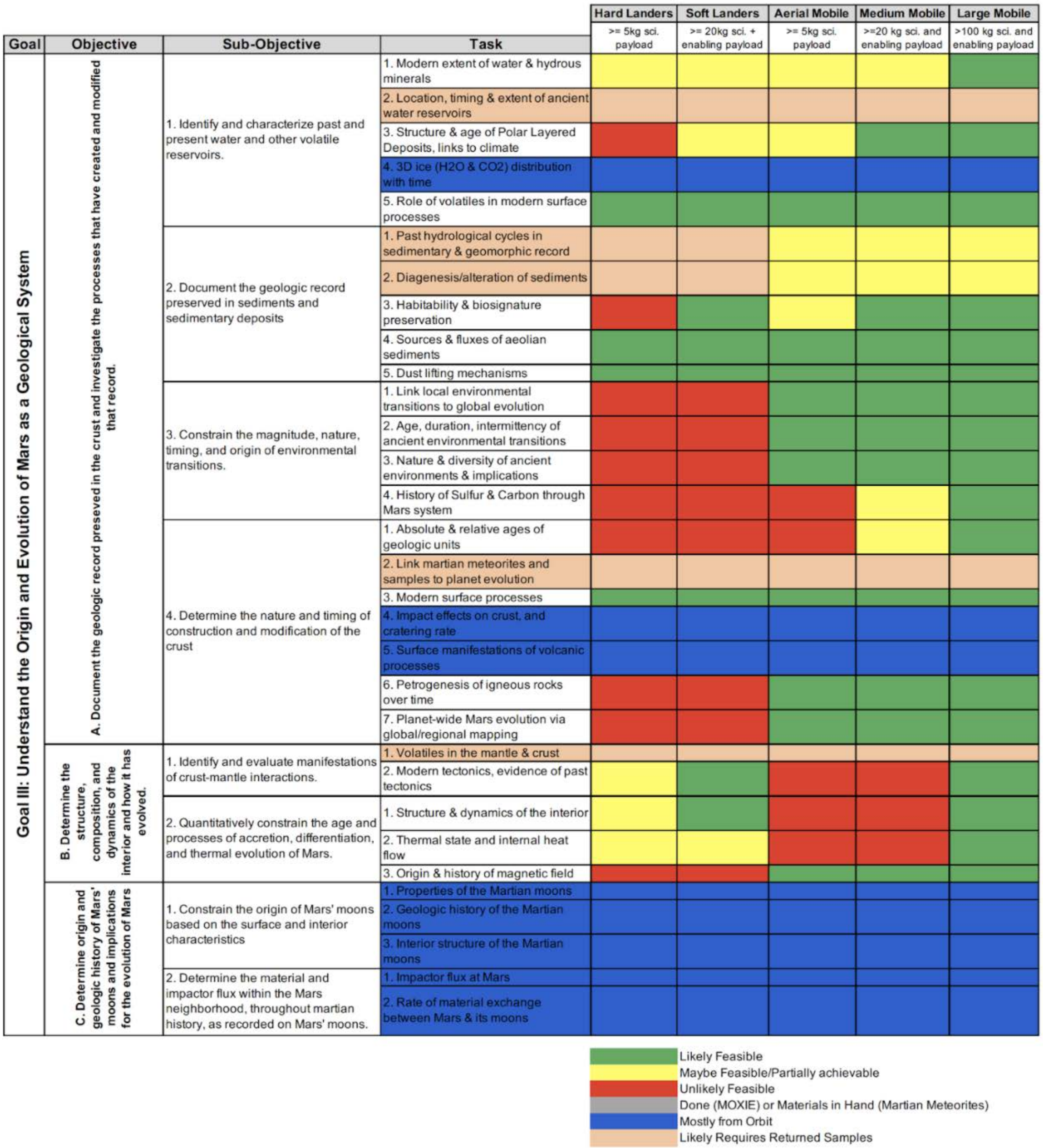


Figure A.3: Goal III (Geology)

Goal	Objective	Sub-Objective	Task	Hard Landers >= 5kg sci. payload	Soft Landers >= 20kg sci. + enabling payload	Aerial Mobile >= 5kg sci. payload	Medium Mobile >=20 kg sci. and enabling payload	Large Mobile >100 kg sci. and enabling payload
Goal IV: Prepare for Human Exploration	A. Obtain knowledge of Mars sufficient to design and implement human landing at the designated human landing site with acceptable cost, risk and performance.	1. Determine the aspects of the atmospheric state that affect orbital capture and EDL for human scale missions to Mars.	1. Global air temperature					
			2. Global aerosol distribution					
			3. Global winds					
		2. Characterize the orbital debris environment around Mars	1. Orbital Debris environment					
		3. Assess landing-site characteristics and environment related to safe landing of human-scale landers.	1. Characterize selected landing sites for hazards					
			2. Geotechnical aspects, chemistry, mineralogy, ice content					
			3. Near-surface winds					
	B. Obtain knowledge of Mars sufficient to design and implement human surface exploration and EVA on Mars with acceptable cost, risk and performance.	1. Assess risks to crew health & performance by: (1) characterizing in detail the ionizing radiation environment at the martian surface & (2) determinng the possible toxic effects of martian dust on humans	1. Assess health risk from neutrons					
			2. charged and neutral particle spectra and dose at surface through solar cycle					
			3. Assay for toxic chemicals in dust					
			4. Dust shape/size potential for eye/lung damage					
		2. Characterize particulates that could affect hardware performance.	1. Regolith & dust corrosivity, charging, conductivity					
		3. Assess the climatological risk of dust storm activity in the human exploration zone at least one year in advance of landing and operations.	1. Dust climatology					
			2. Surface pressure and near-surface meteorology					
			3. Temperature and aerosol profiles even in dust storms					
		4. Assess landing-site characteristics and environment related to safe operations and trafficability within the possible are to be accessed by elements of a human mission.	1. Trafficability hazards of potential landing sites					
			2. Geotechnical characterization of regolith					
			3. Atmospheric electricity, meteorology and dust					
	C. Obtain knowledge of Mars sufficient to design and implement In Situ Resource Utilization of atmosphere and/or water on Mars with acceptable cost, risk and performance.	1. Understand the resilience of atmospheric ISRU to martian conditions.	1. ISRU Oxygen production robustness against dust					
		2. Characterize potentially extractable water resources to support ISRU for long-term human needs	1. Identify usable water resource deposits					
			2. Map an equatorial site with bound water, high-latitude with ice near surface					
			3. Energy required to extract water from near sub-surface					
	D. Obtain knowledge of Mars sufficient to design and implement biological comtamination and planetary protection protocols to enable human exploration of Mars with acceptable cost, risk and performance.	1. Determine niches that are "Special Regions" in the exploration zone.	1. Identify Special Regions					
		2. Determine if martian environments are free of biohazards to humans	1. Is there extant life? Is it dangerous? Can dust move it?					
		3. Determine if martian materials or astronauts have biohazards to Earth	1. Can terrestrial organisms survive exposure to martian material on Earth?					
		4. Determine the astrobiological baseline of the landing site before arrival	1. Determine the astrobiological baseline prior to sending humans					
		5. Determine the survivability of terrestrial organisms exposed to martian surface conditions to better characterize the risks of forward contamination to the martian envoironment	1. Can human bio-material be carried by wind/dust?					
			2. Can terrestrial organisms survive at Mars?					
	E. Obtain knowledge of Mars sufficient to design and implement a human mission to the surface of either Phobos or Deimos with acceptabel cost, risk, and performance.	1. Understand the geological, compositional, and geophysical properties of Phobos or Deimos sufficient to establish specific scientific objectives, operations planning, and any potentially available resources	1. Composition of satellites					
			2. ISRU on satellites					
			3. Gravity field of satellites					
		2. Understand the conditions at the surface and in the low orbital environment for the martian satellites sufficiently well so as to be able to design an operations plan, including close proximity and surface interactions.	1. Regolith properties on satellites					
			2. Determine gravity field for ProxOps & Rendezvous					
			3. Electrostatic charge and plasma fields near satellites					
			4. Thermal environments of satellites					

- Likely Feasible
- Maybe Feasible/Partially achievable
- Unlikely Feasible
- Done (MOXIE) or Materials in Hand (Martian Meteorites)
- Mostly from Orbit
- Likely Requires Returned Samples

Figure A.4: Goal IV (Humans)

A.2 Example Future Landing Sites

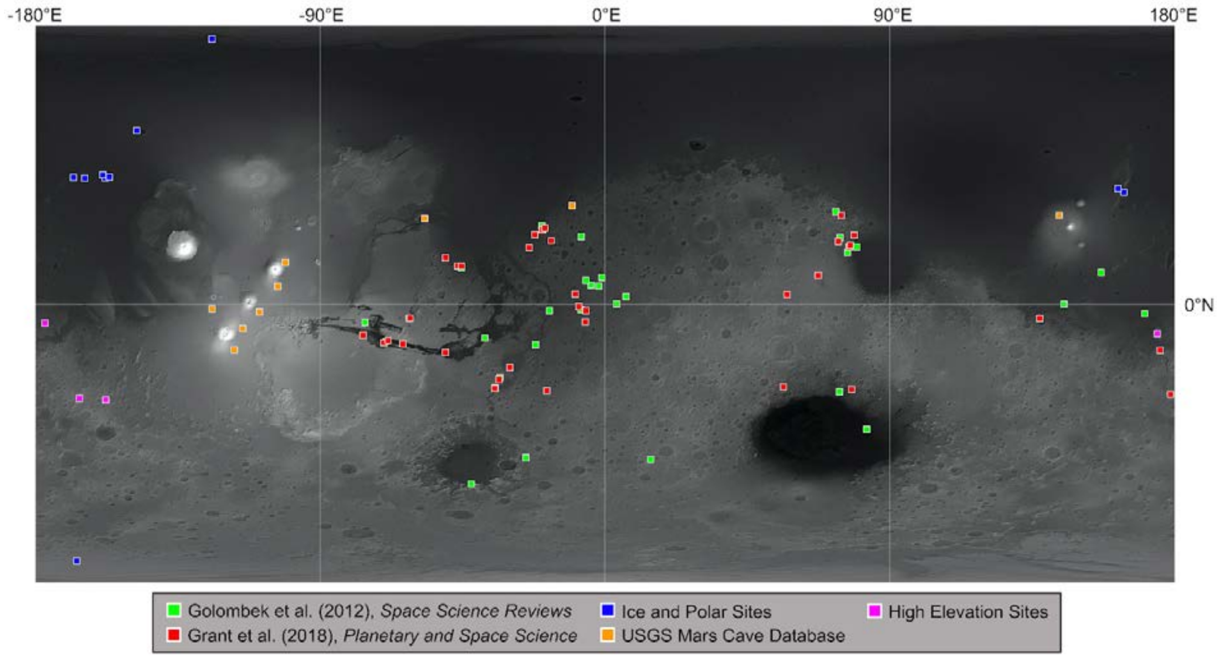


Figure A.5: Locations on the Martian surface that would offer the chance to address new, compelling science through *in situ* exploration highlighted in white papers and scientific publications, as well as in the Mars Science Laboratory and Mars 2020 rover landing site workshops.

A recommendation of this study is that the Mars science community, perhaps under the auspices of MEPAG, retain a database of community-vetted priority landing sites and landing site types for scientific exploration. Figure A.5 shows examples of potential landing sites of interest from community activities to date.

There are a wealth of locations on Mars where we could address new, unanswered science questions with *in situ* exploration but have not yet visited (e.g., Figure A.5). These sites include:

Unexplored past and present habitable environments: Curiosity demonstrated that Gale crater preserved a once habitable fluvio-lacustrine environment (Grotzinger, 2014; Grotzinger et al., 2015), and Perseverance is currently searching for signs of past life preserved in the deltaic deposits of Jezero crater (Mangold et al., 2021). However, we know from orbital data that there have been many different kinds of environments in Mars' past that could have been habitable, as well as limited locations today that might still be habitable. Exploring these sites would address outstanding questions about the presence of extant and extinct life on Mars.

Example sites: *Hydrothermal hot spring systems like the Nili Patera, Leighton Crater, or the Columbia Hills, which were explored in situ by the Spirit rover, but not with a payload capable of searching for biosignatures (e.g., Grant et al., 2018 and references therein). Decameter scale mineralized veins visible in Northeast Syrtis or groundwater fed lakes at McLaughlin Crater provide surface links to subsurface aquifers, which are also potentially habitable environments that have not yet been explored (Michalski, 2019; Quinn and Ehlmann, 2019). Deep sulfate lakes and recent shallow chloride ponds preserved in high elevation Terra Sirenum (Leask and Ehlmann, 2022). Modern habitable environments may also be present in Martian caves formed in lava tubes, which provide shielding from radiation and more stable thermal environments than the surface (e.g., Léveillé and Datta, 2010).*

Records of planetary evolution and ancient climate change: Our knowledge about the evolution of Mars' atmosphere and climate is limited by the time-history exposed in the Martian landing sites we have explored to date. We have not yet visited sites with expansive rock records older than ~3.7 Ga, a time period that encapsulates dynamic change in Mars' atmospheric pressure, volcanism, magnetic field, as well as the formation of giant impact basins in Utopia, Hellas, and Isidis. We have also not yet explored sites with specifically exemplary preserved examples of Martian volcanic and crustal evolution, or clearly preserved magnetic fields.

Example sites: *Ancient basement crustal rocks in NE Syrtis/Nilli Fossae. Proposed subaerial weathering profile at Mawrth Vallis or on the plains surrounding Valles Marineris that could preserve information about atmospheric composition. Valley network deposits to estimate rates and discharge volume, which link to climate. Preserved magnetic stratigraphy and distinctive volcanism in the Lucas Planum (Apollinaris patera) area.*

Records of modern climate change, Mars' volatile cycles, and *in situ* resources: The ices found in the unexplored Martian polar and high latitude regions hold Martian climate and volatile history. In particular, the layered Martian polar deposits contain a climate record of the past millions to hundred of millions of years in Mars' history. Accessing this record requires *in situ* measurements of the deposits' compositions, including isotopic measurements, stratigraphy, deposition, erosional, deformational and melting history, and evidence of long-term exchange with ice deposits across Mars. Exploring both polar and high latitude ice deposits would also allow characterization of *in situ* resources for future crewed exploration.

Example sites: *Widespread ground ice in Arcadia Planitia, exposed ice scarps in Milankovic Crater, scarps visible in the North Polar layered deposits (Bapst et al., 2021; Bramson et al., 2015; Golombek et al., 2021; Russell et al., 2008)*

A.3 Small and Networked Landers

There is key science that remains undone – but is doable – at the smallest lander mission class that does not require mobility (Section 5.2). Small and networked lander missions bring particular scientific value in coordinated measurements, key for select topics. Networked landers can return spatial and temporal variations of atmospheric and meteorological data (Linkin et al., 1998), seismological data to infer the planet's internal structure, measurements of magnetic field strength and subsurface water, and provide point compositional measurements. In this section, we provide a brief overview of the history of small and networked lander missions in order to highlight the science questions these platforms addressed or were envisioned to address, and discuss lessons learned that should inform plans for future Mars lander programs as part of the FAB strategy.

The first proposed networked landed mission was started in 1988 with the Mars '96 mission. Until 2016, other networked landed missions were frequently proposed. However, few of these missions were launched; some were rejected after Phase A study. Others simply lost funding momentum for reasons outside of their control or failed to be deployed.

Mars '96: Mars '96 (Roscosmos) was a Mars mission launched in 1996, which included two small stations, two penetrators, and an orbiter. Roscosmos had the primary responsibility of the mission, and the Finnish Meteorological Institute (FMI) and CNES collaborated on the realization. Unfortunately, Mars '96 was launched into Earth orbit but failed to be inserted into Mars cruise trajectory, impacting Earth's surface. Mars '96 aimed to investigate the evolution of Mars, specifically, the atmosphere, surface, and interior evolution. The network was supposed to land on the Amazonis-Arcadia region, where the two small stations would have been separated from the main orbiter five days before Mars arrival and approached the planet independently; during entry, atmospheric measurements would have been acquired. The penetrators, instead, were to be released by the orbiter from Mars orbit and placed by a solid rocket into an atmospheric entry trajectory.

Mars Environmental SURvey (MESUR): MESUR (NASA) aimed to establish a global network of 16 small stations simultaneously active for one Martian year. The landers would have, indeed, provided pole-to-pole coverage of Mars.

MESUR's scientific objective was to characterize the Martian environment, specifically, the atmospheric structure and circulation, internal structure, and chemistry and morphology of the surface. The 16 landers would have been launched over four launch opportunities, creating two seismic triads and one seismic pair. The stations landed first were required to endure for at least three Martian years. MESUR Network would have worked in conjunction with Mars Observer, preceded by MESUR Pathfinder, a larger single-spacecraft mission for technology testing. However, in 1994, in the wake of the Mars Observer failure, NASA stopped funding the MESUR network. Pathfinder's work continued under NASA's low-cost Discovery Program.

Marsnet: Marsnet was a mission selected by ESA for a Phase A study. The mission conceived the creation of a regional network of three or four stationary semi-hard landers. The network would have been able to collect information about the internal structure of Mars, the mineralogy and chemistry of rocks and soil, and the atmospheric circulation and weather. Moreover, Marsnet was designed based on a possible collaboration with MESUR, enabling a global Mars Network. The two missions would have complemented each other in their mission implementations and science. Unfortunately, the mission ceased to exist after the completion of Phase A.

Intermarsnet: Intermarsnet was a joint ESA/NASA mission, which aimed to create a regional network of landers. The objective of the mission was to study the interior, surface, and atmosphere of Mars. In this joint effort, ESA would have provided the launcher, the orbiter, and the launch support structure, while NASA would have provided the three landers. The conceived mission design involved three Free Flyer Landers and a Mars Orbiter, launched together on a dedicated Ariane 5 in June 2003. After insertion in interplanetary orbit, the Orbiter and the Free Flyers would have been separated. Each lander was to land using an aeroshell, a parachute descent system, and an active propulsive system.The mission was canceled due to a considerable reduction of the European budget for the ESA science program and a NASA distraction by domestic pressures to achieve other scientific objectives (ESF–NRC et al., 1998).

Deep Space 2: The Deep Space 2 (NASA) was a technology demonstration composed of two probes piggybacked by Mars Polar Lander. Deep Space 2 aimed to demonstrate innovative and low-cost approaches to land on a planet using only a heat shield. The two probes were attached to Mars Polar Lander, separated ten minutes before touchdown, and crashed into the Mars surface. The mission was launched December 3, 1999; however, Mars Polar Lander failed to land safely, and communication with Deep Space 2 probes was never established after their impact.

NetLander: The NetLander (CNES/ESA) mission included four landers intended to produce a regional network on Mars. The mission aimed to study the interior, the atmosphere, the subsurface, the ionospheric structure, and the geodesy of Mars. CNES managed the mission, but many other institutions, i.e., DLR and FMI, were collaborating. In addition, the mission was to use rideshare on Ariane 5 dedicated to launching some Mars Sample Return mission elements. The mission was canceled in the early 2000s after the NASA withdrew support following the failure of Mars Polar Lander (staff, 2003).

Mars MetNet: Mars MetNet is a planned science mission by the Finnish Meteorological Institute (FMI), Lavochkin Association (LA), Space Research Institute (IKI) and Instituto Nacional de Tecnica Aerospacial (INTA), in which the main objective is to land a global network of small stations on Mars using a new type of semi-hard landing vehicle. The main scientific objective of Mars MetNet is to collect data for atmospheric model verification and weather forecasting, which will help in safely landing large masses. The 16 landers will be landed on Mars using inflatable entry and descent systems with a payload-mass fraction of approximately 17%, composed of two Inflatable Braking Units, which will crush and penetrate the main body into the soil of Mars. In 2019, the full qualification model (QM) of the MetNet landing unit was the Precursor Mission underwent functional tests (Harri et al., 2019).

Comparison and Lesson Learned

The state-of-the-art over the decades demonstrates a great interest in missions whose scientific objectives focus on seismology and meteorology. Data of the atmospheric vertical structure are also considered fundamental for the future of Mars exploration and the landing of large masses.

Moreover, the analyzed missions agree that seismological and atmospheric science missions require stationary or low-mobility landers networks, typically of $\geq$3 and up to 16, lasting at least 1 Martian year to provide enough spatial and temporal data.

However, the design of these missions reports a large variability between numbers of landers, landers mass, transfer method, and EDL system. Indeed, the specific choice was dependent on the available funding, international collaboration, status of other primary Mars missions, and technological capabilities of the country leading the mission.

Another trend suggested by direct comparison of the missions lies on the landed mass. Mass tended to slowly increase from 1988 to 1996, with a peak reached with Intermarsnet, followed by a consequent drop in designed landed mass. The two reasons for the heavy mass of Intermarsnet lander are the availability of additional funding due to the international collaboration and the simultaneous development of Mars Surveyor 98, which design would have been imitated. Also, the increase in complexity is in line with the evolution of the faster, better, cheaper approach. Interestingly, the following reduction of mass size may be due to technology advancement and a more compressed space budget.

Historical missions also reveal that the need for international cooperation has been considered fundamental for achieving a solid science objective (MESUR + Marsnet), and its lack has often been the reason for missions cancellation (Intermarsnet). However, the fickle space budget remained the principal reason for landed network missions' high early mortality.

The scientific community was looking towards developing more affordable landing options, as testified by the development of the aeroshell impactor of Deep Space 2 and the inflatable braking units of Mars MetNet. Furthermore, the comparison highlights how networked landed missions can be successfully developed only by following a low-cost approach. Indeed, some mission proposals like MESUR with its 16 landers or Intermarsnet with ~400 kg lander and retro propulsion system for soft-landing were too ambitious for a low-cost mission concept.

Finally, Deep Space 2 arose from a shifting philosophy: "Taking risks to reduce future danger" and is one of the FBC missions. Although this philosophy aligns with the idea of increasing risks distinctively shared in this report, the Deep Space 2 philosophy did not fully account for mission variability to achieve success. The two probes followed the same entry profile to crash into the surface of Mars without telemetry data to understand the reasons for their fate. Therefore, it would have been preferable to include telemetry or some variability in the most challenging mission phases to increase mission success despite increasing mission risks.

Name & Years	**Mars '96 [1,2,3] 1988-1996**	**Marsnet [4, 5] 1991-1993**	**MESUR [6, 7, 8] 1990-1994**	**Intermars Net [9,10] 1996**	**Deep Space 2 [12] 1996-1999**	**NetLander [13, 14] 2006-2009**	**MarsMetNet [15-17] 2009-2016**
Agency	Roscosmos + FMI + CNES	ESA (Collab. with MESUR)	NASA Ames-JPL	ESA/NASA	NASA JPL	CNES/ESA	Finnish Meteorological Inst.
Scientific Goal	Seism. & Meteorology - Atmospheric	Seism. & Meteorology - Atmospheric	Seism. & Meteorology - Atmospheric	Seism. & Meteorology - Atmospheric	High-risk tech. dem. - Atmospheric & water ice search	Seism. & Meteorology - Atmospheric	Atmospheric Structure & Meteorology
Science Start	S.:during descent P: after landing	During descent	During descent	During descent	During descent	During descent	During descent
Landers Number	4	3 or 4	16	3	2	4	16
Launches Number	1	1	4 Each launch 4 stations	1	1 - With Mars Polar Lander	1 Ariane V - Mars Sample Return	-
Type of Landers	2 same stationary small stations (S) 2 same penetrators (P)	Stationary - all the same	Stationary + small rover instrument - all the same	Stationary + small rover instrument - all the same	Stationary - impactor - all the same	Stationary - All the same	Stationary - impactor - all the same
Distribution	Regional (Amazonis-Arcadia Region)	Regional (Tharsis Region)	Global (RTG use) 3 regional seismic net.	Regional (Tharsis Region)	Regional	Global 1 seismic triad + 1 opposite.	Global
Lander Mass	S.: Entry mass 87kg At M. (w. airbags) 33kg P.: 45kg	Entry mass: 117kg At M: 87kg	Entry mass: 159kg	Entry mass: 415kg	Entry mass: 3.5kg	Entry mass: 66kg At M: 22kg	Entry mass: 16.8kg At M: 8.9kg

Name & Years	Mars '96 [1,2,3] 1988-1996	Marsnet [4, 5] 1991-1993	MESUR [6, 7, 8] 1990-1994	Intermars Net [9,10] 1996	Deep Space 2 [12] 1996-1999	NetLander [13, 14] 2006-2009	MarsMetNet [15-17] 2009-2016
Payload Mass	S.: 12kg P.: 4.5kg	8.4kg	-	15kg	-	5.2kg	4kg
EDL	S.: Heat Shield (HS) + subs. Parach. + Airbags P.: P. Rocket burns (to place into entry trajectory) + HS + Parach.	Unguided ballistic entry with semi-hard landing (HS + trans. and sub. Parach.)	HS + subs. Parach. + Airbags	HS + hypers. Parach + propulsive engines (controlled by beam radars)	HS shuttered upon impact.	HS + hypers Parach. + Airbags	Two Inflatable Braking Units
Cruise	S.: separated from S/C 4-5 days before Mars (M) insertion. P.: deployed from M. orbit S/C	Separated from Multiple Probe Carrier 4-2-1 days before M. insertion.	Placed stations towards M. After, each s. cruises alone as indep. free-flyer.	Placed stations towards M. After, each s. cruises alone.	Piggyback with lander - separation 10 mins before touch-down.	Separated and targeted from SC 5 days before M. insertion.	Or piggyback or dedicated launch with orb
Mission Lifetime	½ Martian year	1 Martian year	1 Martian year (First stations 3 Martian years survival)	1 Martian year	36 hours + until battery lasted	1 Martian year	3.5 Martian years
Status	Launched and Failed	Cancelled	Cancelled Only MESUR Pathfinder launched	Cancelled	Launched and Failed	Cancelled	Unknown

Table A.1: A tabular approach to the information presented in the previous subsection allows for a direct comparison between the missions.

A.4 Historical Faster, Better, Cheaper at Mars

The 1980s to 1990s was a period of relatively little activity in robotic planetary exploration and the missions that were conducted had a high per unit cost. Faster, Better, Cheaper (FBC) was a philosophy adopted by NASA from 1992 to 1999 to manage programs and projects, which resulted in 16 launches of small, low-cost robotic spacecraft (McCurdy, 2003). The goal of FBC was to reduce the mission time and cost while increasing its scientific return and the overall number of missions. However, after the failure of four FBC missions (WIRE, Mars Climate Orbiter, Mars Polar Lander, and Deep Space 2), the approach was abandoned, and the paradigm shifted back to "Mission Success First" (Gross, 2001; Mars Climate Orbiter Mishap Investigation Board, 1999).

A.4.1 Historical Context

FBC was initially introduced by NASA Administrator Daniel Goldin, appointed by the White House in 1992. The White House wanted to reform NASA to transform its old high spending culture and selected Goldin because of his work in small, low-cost spacecraft. Until 1992, space missions were developed using the "Apollo-era" methodology, which included functional redundancy and military hierarchical project management techniques (Johnson, 2006). Because of the high costs and schedules, NASA did not launch any planetary mission between 1978 and 1989 (Frank, 2019).

When appointed, Goldin stated: "There's a paradox at work here that creates a downward spiral. Launching fewer spacecraft means scientists want to pile every instrument they can onto whatever's going to fly. That increases the weight, which increases the cost of the spacecraft and the launcher. Fewer spacecraft also means we can't take any risk with the ones we launch, so we have to have redundancy, which increases weight and cost, and we can't risk flying new technology, so we don't end up producing cutting-edge technology" (McCurdy, 2001).

The FBC slogan was: "It's OK to fail," and Goldin's perspective was that if the overall number of missions increased while taking calculated risks, failing a few missions would have been acceptable (Dillon and Madsen, 2015; NASA FBC Task Force, 2000).

Initially, FBC was applied with great success. However, after a string of failures in 1999, NASA abandoned the approach (McCurdy, 2001).

A.4.2 The Philosophy

FBC is composed of the three words: Fast, Better, Cheaper; specifically, "Fast" refers to reducing the mission cycle, "Better" means a higher scientific return per dollar spent, while "Cheaper" clearly indicates a reduced mission cost. To this end, FBC aimed to (1) create smaller spacecraft and more frequent missions; (2) reduce cycle time by eliminating inefficiencies; (3) utilize new technology; (4) accept moderate risk for warranted scientific return; and (5) utilize proven technology (i.e., COTS).

According to McCurdy (2001), history and collected data show that spacecraft cost and cycle time can be reduced without significant loss of reliability and with a modest decrease in spacecraft capabilities. Furthermore, this process can be accomplished through 1) miniaturization of the technology, which reduces the size of the spacecraft used; and 2) less complex and less expensive project management. Moreover, lower mass decreases costs and spacecraft complexity, allowing fewer people to work on a simpler project, where workers can resolve reliability problems through face-to-face communications. McCurdy identifies two causes for the failure of 1999: 1) an increase in the mission complexity with a disadvantaged cost and schedule resources; 2) a lack of system management necessary to assure that the teamwork controls reliability (McCurdy, 2001).

Following the failures of 1999, the Mars Program Independent Assessment Team and MCO Mishap Investigation Board reports identified some findings in their independent reviews. Specifically, they identify 1) inadequate risk management tools; 2) inadequate training and mentoring of new employees; 3) lack of communication of noticed problems (Gross, 2001; Mars Climate Orbiter Mishap Investigation Board, 1999). Also, the Mars Program Independent Assessment Team recognized the insufficiency of policy and guidelines, which make it impossible to attribute a clear line of responsibility for managing risks. Specifically, the report states: "The FBC initiative has changed the way NASA does business, but it has not been adequately defined in NASA's policies and guidance or strategic planning process" (Gross, 2001).

A.4.3 The Missions

16 FBC missions were launched between 1996 and 1999 ((McCurdy, 2003) under 5 NASA Science Mission Directorate Programs that spanned planetary science, Earth observation, and astrophysics (Gross, 2001):

Discovery Program

Near Earth Asteroid Rendezvous (launched in February 1996)
Mars Pathfinder (launched in December 1996)
Lunar Prospector (launched in January 1998)
Stardust (launched in February 1999; returned comet material to Earth in 2006)

New Millennium Program

Deep Space 1 (launched in October 1998)
*Deep Space 2 (launched in January 1999 with Mars Polar Lander; lost during failed Mars

Polar Lander atmospheric entry)

Mars Surveyor Program
Mars Global Surveyor (launched November 1998)
*Mars Climate Orbiter (launched December 1998; failed to enter Mars orbit)
*Mars Polar Lander (launched January 1999; failed during Mars atmospheric entry)

Small Explorer Program
Solar, Anomalous, and Magnetospheric Particle Explorer (launched into Earth orbit in July 1992)
Fast Auroral Snapshot Explorer (launched into Earth orbit in August 1996)
Submillimeter Wave Astronomy Satellite (launched December 1998)
Transition Region and Coronal Explorer (launched into a sun-synchronous orbit in April 1998)
*Wide-Field Infrared Explorer (launched in March 1999; failed in space)

Small Satellite Technology Initiative
*Lewis (launched in August 1997; failed in space four days after launch)
*Clark Earth Observing Satellite (canceled in February 1998)

*Missions marked with an asterisk were considered failures (five spacecraft failed in space; one project was canceled).

The most apparent mission accomplishment using the FBC approach has been Mars Pathfinder (1996), which landed a lander and a rover on the surface of Mars for $265M ($487M in FY '22) in only three years of cycle time. NASA was already successful in landing on the Martian surface with the two Viking spacecraft in 1976. However, the Viking mission cost $1.06B and launched in 6 years ($7.2B in FY '22). To achieve this reduction, the Mars Pathfinder team: 1) delivered a lighter total mass mission (lander and rover mass); 2) accepted risks that Vikings' team had not (landing technique, lack of redundant lander); 3) reduced the amount of science that the spacecraft could perform; 4) used commercially available technology; 5) employed fewer people (McCurdy, 2001). Table 2 identifies and summarizes the principal saving motivations and their relative amount with respect to the Viking mission.

Categories	Saving Amount
Launch Cost	$240 million
No Orbiter, less Scientific Instruments, Shorter Operations Time	$1,038 million
Smaller Team for In-Flight Operations	$174 million
Leaner Workforce - Fewer Employs	$161 million
No Cost Overruns in Technology Development, use of COTS	$545 million
Single Lander with Basic Flight System vs Two Landers for Vikings	$1.5 billion

Table A.2: Savings Allocation of Mars Pathfinder Mission with respect to Viking Mission (in inflation-adjusted dollars; McCurdy, 2001).

A.4.4 FBC Success

FBC was considered successful between 1992 and 1998, where the first nine out of ten missions launched were successful (90% success rate). After 1999, however, NASA abruptly abandoned the FBC approach, when four of the five following missions failed (67% combined program success rate).

Nevertheless, FBC cannot be properly evaluated using solely the mission success rate, since FBC consciously embraces a higher likelihood of mission failure in favor of reduced cost and mission cycle. The measure of success should include more indicators, i.e., mission outcomes, scientific return, overall cost. Analysis has shown that FBC resulted in more scientific publications per dollar of mission cost than other types of missions. Interestingly, the failed missions also resulted in scientific articles and citations, suggesting that failed missions also hold science and engineering value (Dillon and Madsen, 2015).

According to Rob Manning, Engineering Fellow at JPL and Mars Pathfinder Chief Engineer, "while difficult to find, there is a 'sweet spot' that the early FBC missions were able to find that led to reasonable success rates. With each new FBC mission, the complexity and scope per dollar grew, while the personnel experience levels per project shrank." He also stated, "It is hard to go completely back, though. None of the FBC missions were required to thoroughly document what was tested, nor investigate and fully document all the risks. Spending federal dollars now comes with the added burden to justify what was done and why. Failure needs an explanation. If MPF had failed, I only had my notebooks and my memory to justify what I did. We would have been in big trouble. It is a different world today. But appropriate and innovative FBC is still a possibility, and we shouldn't be afraid of it" (Frank, 2019).

A.5 Ways to Reduce Cost

The topic of reducing cost for space missions and other large technical programs has been broadly and widely studied, and a thorough accounting is well beyond the scope of this report. The workshop's recommendations around an affordable Mars surface exploration program are summarized in Section 3.2. That said, practical methods for reducing the cost of space missions are key to implementing a Frequent, Affordable, and Bold Mars strategy, so this appendix presents some of the recurring themes and most useful resources that were discussed at the workshop.

The **"space spiral"** shown in Figure A.6 (from Wertz et al., 2011) summarizes the situation at a programmatic level. Long development timelines and a small number of missions lead to a demand for higher reliability for each mission, and all of the above increase the cost per mission. That high cost further reduces the appetite for a larger number of missions, and the cycle continues. The good news is that the cycle can run in the other direction as well, and this positive feedback cycle can be kickstarted from any point.

Figure A.6: (A) and (B) show the negative and positive reinforcement cycles, respectively, associated with the cost of space missions (from Wertz et al., 2011).

As reflected in Figure A.6, **cost is largely driven at a programmatic level.** Consider cost as divided into four general categories as shown in Table A.3. For most programs a large portion of the total cost, perhaps 60%, is spent on non-recurring engineering. This is in part simply because most of the money for a space mission is spent paying salaries. Wayne Hale sums up this phenomenon with an in-joke from the Shuttle program office: "The first Shuttle launch of the year costs $3 billion; all the rest of the flights are free (Hale, 2019)."

Contractual Deliverables	Non-Recurring Engineering	Recurring Engineering
Data Items (paperwork)	Plans, analyses, designs, procedures, reviews	Reviews, reports
Configuration Items (product)	Ground support equipment, development models, factories	Flight models

Table A.3: Cost categories for a space mission.

The **contracting structure** applied to a program has a major impact on cost, and constrains programmatic decisions. Fixed cost contracts are one way to reduce some of the required paperwork (and associated labor) while still operating under the Federal Acquisition Regulation (FAR) rules, effectively transferring the risk associated with cost uncertainty from the government to the contractor (Wooster, 2007). Other approaches, such as Space Act Agreements and paying for a service instead of buying hardware, have the potential to further streamline acquisition and reduce cost to the government. These approaches have proven successful in the programs for commercial cargo and crew resupply to the International Space Station.

NewSpace, defined in contrast to traditional aerospace prime contractors, is a bit of a buzzword with varying definitions but (NewSpace citation) provides a reasonable point of reference for what sets these businesses apart. NewSpace avoids cost-plus contracts and the associated overhead. There is a strong focus on low cost, ideally achieved by pursuing high-rate commercial markets that lead to economies of scale. NewSpace tends to make greater use of commercial off-the-shelf (COTS) parts, believing that high reliability demonstrated in terrestrial environments will provide adequate reliability for many space activities. Careful use of redundancy and fault tolerance will further reduce the reliance on higher priced space heritage parts.

Small, empowered project teams and minimal paperwork also enable these faster development times. As stated in (Wertz et al., 2011), "The real secret to reducing space mission cost is to empower individuals and small teams, motivate them to reduce cost, reward them for achieving it, and then get out of their way." NewSpace can refer to a Skunk Works style group within NASA or larger, traditional aerospace contractors as well as entire companies. That said, to quote cost modeler Al Nash, "The Venn diagram of New Space cost and Old Space customization is the null set."

Economies of scale or **bulk buys** are cost reduction methods not often achieved in planetary exploration, but there are some success stories from Earth-orbiting spacecraft. One key is clear demand signaling: for cost savings to be realized, a contractor has to know ahead of time that they will be building N copies of something, not asked for another "build to print" years later. The traditional learning curve for economies of scale is perhaps more representative of assembly line-style mass production than space exploration where even a dozen copies is a lot, but the amortization of research and technology development over N builds still provides a significant opportunity for cost reduction.

COTS hardware and software offer a potential for major cost reduction by not reinventing the wheel. The industry that has grown around CubeSats offers increasingly capable parts that are already space qualified, at least for low-Earth orbit. Automotive parts may be available to perform a desired function, and are often mass produced and tested through high usage rates. A recurring theme during the workshop was making it easier and less expensive to space-qualify automotive and other COTS parts. One way to do this is by spending spacecraft mass to accommodate parts within their certified environment, rather than spending money to certify for a new environment.

Standardization and **simplification** can be effective cost reduction strategies. In particular, eliminating requirements or entire subsystems is the fastest path to a simpler, less expensive spacecraft. Remaining requirements should be functional and specify what is desired, not how it will be achieved. The number of interfaces tends to be a major cost driver, especially when it comes to multiple instrument payloads. It should also be acknowledged that standardization and optimization (or minimization of margins) can be opposing forces (Wertz et al., 2011); using large margins or reduced requirements to enable use of standardized interfaces, parts, or entire buses is a path to reducing cost.

Specific ideas for **improving affordability of mobile platforms for the Martian surface** were considered by one of the workshop's working groups. Perhaps unsurprisingly, no "magic bullet" was identified that would dramatically reduce the cost of a single MER-style rover under the current paradigm and culture. For a rover, incremental cost reduction methods include: eliminating the mast and using the robotic arm for its functionality instead; swap-out capability for arm-mounted tools; a 4-wheel skid-steer rover that avoids obstacles instead of requiring capability to drive over them; and increased autonomy to reduce operations costs. Mars helicopters were also considered as a mobility platform that could potentially have higher capability/cost ratio than a rover for some applications. A major benefit is that for the same distances, a helicopter could have lower mass and achieve longer traverse distances. If the helicopter can deploy mid-air during EDL, the descent and landing subsystems can be eliminated along with their price tags. For both of these systems, cost reduction to the cruise stage (which has strong standardization potential) could be significant for the overall program cost. Increased use of COTS parts and elimination of EDL subsystems were seen as the most promising overarching cost reduction strategies for this mission class.

A.6 What Does Starship Change: What Breaking the Mass-Cost Relationship Could Achieve

Traditional space mission development costs are frequently correlated with increasing mass; as hardware increases in mass, it also increases in cost and complexity. This relationship rests on the assumptions that launch costs per kg are high and that there is a strong incentive to take advantage of every kg available. Higher mass payloads would then allow for more complex and more capable systems that in turn result in much higher costs.

This relationship between mass and cost is not a necessity, but rather is incentivized by high launch costs. If the launch costs are instead assumed to be low, and that available payload mass is very high, the ability to fly high mass/low cost payloads becomes much more tractable. There are several ways to potentially reduce cost in a payload that is unconstrained in mass (Table A.4).

Approach	Description
COTS	COTS equipment leverages economies of scale on Earth providing substantial cost-savings.
Shielding/Insulation	Shielding and insulation can help payloads meet thermal and radiation requirements but are frequently impractical for extensive use on space missions due to mass constraints.
Communications Infrastructure	Large, massive antennas can be enabling for communications and are frequently impractical due to mass/volume constraints on space missions.
Solar Power and Batteries	Scaling up solar power relies on increasing the quantity of solar panels, which in turn increases mass. More solar panels provide more power which can enable COTS equipment that require more power than is typically available on space missions

Table A.4: How to use mass to save Money.

The use of commercial off the shelf (COTS) payloads is perhaps the best way to obtain massive cost savings in an unlimited mass environment. COTS leverages the production and development paid for by large markets on Earth to provide robust products that are highly capable. Mass is a very common limitation for using COTS parts on space missions, but is not the only reason. Environmental factors can also be very important given the hostile environments in which spacecraft operate. Therefore adding additional shielding, heaters, and insulation can help alleviate these problems. Since mass is not a limiting factor, large amounts of heating and insulation can help maintain temperatures. Also, adding shielding can provide protection from harsh radiation environments. One factor that might be missing in the application of many COTS products to Mars is autonomous operation. However, that is increasingly being incorporated in many products as artificial intelligence systems have developed for many industrial applications, e.g., self-driving cars.

Commercial solar power products can potentially be utilized on the surface of Mars to provide much more power than is typically available if mass is not a constraint. Products are available that can substantially simplify deployment, and structures can be easily constructed to take advantage of these products.

Finally, large communications infrastructure pieces can be combined with abundant power to create high data downlink rates. A large communications dish and array could potentially be installed on the Martian surface to provide a much more capable communications link to Earth that could far outstrip any equipment currently in orbit for fractions of the price.

A.6.1 Case Study: Adapting a Commercial Off the Shelf Electric Vehicle for Mars

Assumption: Delivery of 5 tons to the surface, including rugged COTS Electric Vehicle

The recent revolution in electric vehicles may pave the way for direct application to Mars. Commercially available electric vehicles have a number of features that make them more suitable for driving on Mars than older internal combustion vehicles, particular in situ fueling options (solar, gas ISRU). Thermal is probably the biggest challenge. On Mars the temperatures are much colder (-100°C to 20°C at the equator; and down to -128°C at the poles) than the coldest locations on Earth (-89°C), but the thin atmosphere on Mars could mean that overheating may be a bigger problem than cooling. Newer electric vehicles have more robust thermal control to maintain battery temperatures, and additional mass could be used to substantially augment such systems. Commercial electric vehicles are also robustly constructed to withstand vibration and stress, similar to aerospace vehicles. Pressures on Mars are much lower than Earth (10 mbar vs. 1000 mbar), which are outside the testing ranges for sealed fluid-filled parts on electric cars. For tires that are typically pressurized to 2 to 3 bars of pressure, the difference would likely be within tolerances (Although more robust solid state tires may be preferred given the lack of tire changes on Mars). Similarly for other sealed and pressurized components, the pressure difference between Earth and Mars is likely to be within design tolerances.

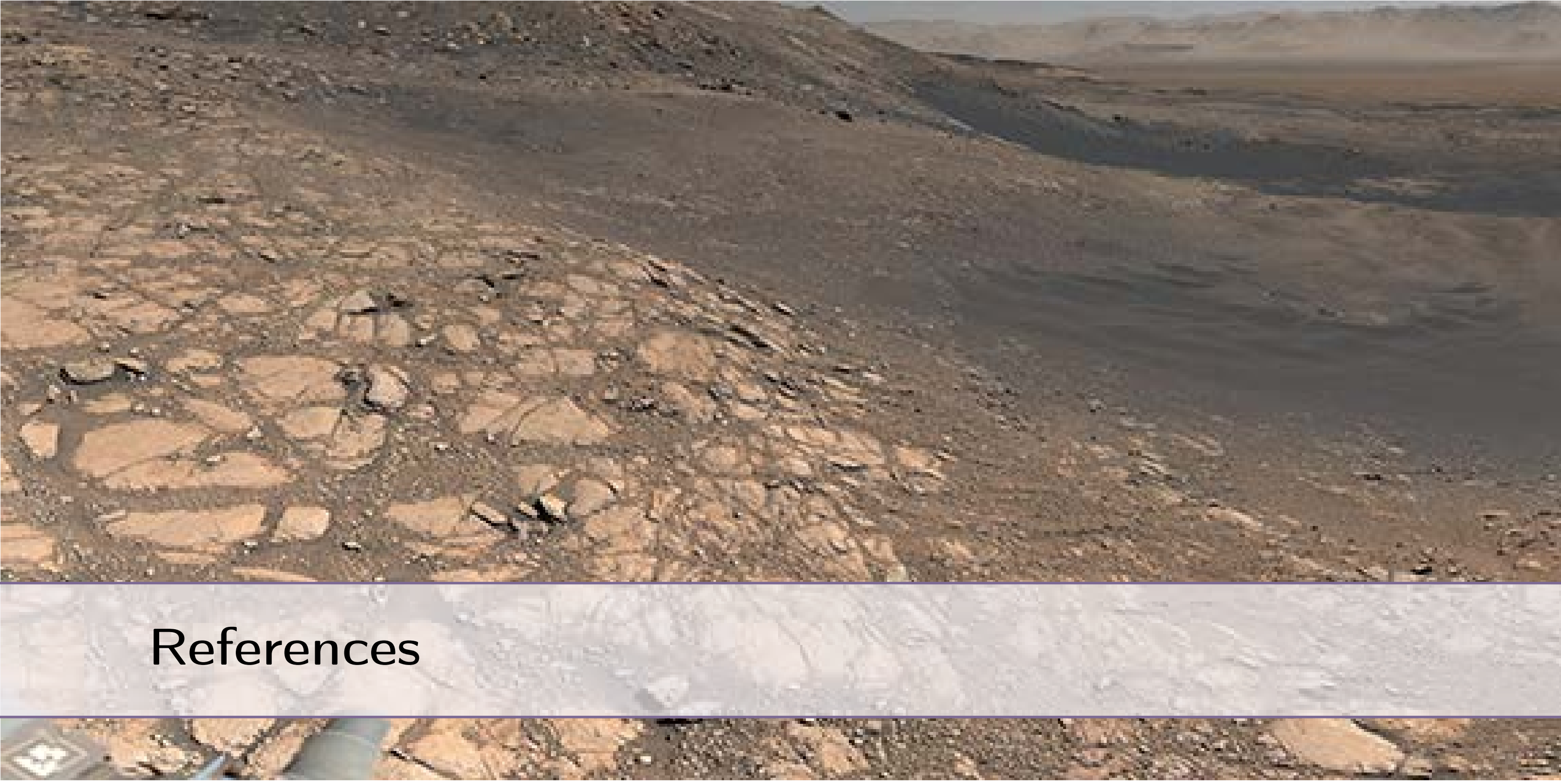
Adapting an off-road capable electric vehicle to driving on Mars may require some reasonable modification including tires, ground clearance, communication, and autonomy. The lack of cell networks and GPS on Mars would necessitate a customized communications solution for communicating with the vehicle, but this could be overcome with standard comm relay via orbiter, multiple times of day, as with existing missions. Fortunately many new cars do not require continuous operator attention and have already developed "self-driving" capabilities which include steering control and robust sensor arrays, allowing leveraging these existing systems for a functional driving capability. Furthermore, enhancements to off-road capabilities of these vehicles (common modifications by after market retailers) could allow them to be extremely risk tolerant and capable of driving on most of the terrain on Mars.

Finally, communication and science payloads would have to be integrated, and these might be the highest cost modifications of the vehicle. Mars science payloads typically average $10s M which is 10–100 times more expensive than the electric vehicle itself. On the other hand, the overall mission cost would still be 1-2 orders of magnitude lower.

Testing and qualifying this vehicle for the Martian environment could incur substantial cost to the development; however, if recommendations from this report are adopted, lower cost and higher risk should be emphasized in order to capture extraordinary capability (Table A.5). A higher risk approach could forgo extensive testing especially if this vehicle is included on a high risk lander, instead favoring multiple builds of science instruments so that multiple mission attempts provide resiliency.

	COTS Electric Vehicle	Perseverance Rover
Cost	<$100,000*	$2.2 billion
Battery Capacity	70-100 KWh	19.3 KWh
Range	200+ miles, single charge	20+ miles
Speed Range (terrain dependent)	0-150 mph	0-0.075 mph
Weight	2-2.5 tons	1 ton
Payload Capacity	450 kg	60 kg
*Cost does not include payload or modifications to off-the-shelf vehicle capability		

Table A.5: Comparison of typical commercial electric vehicle to Perseverance Mars Rover.



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