Mars In Retrograde

A Pathway to Restoring NASA's Robotic Mars Exploration Program

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Executive Summary

From its inception in 2000, NASA's Mars Exploration Program has enabled the space agency's leadership to define a coherent scientific and engineering strategy for its robotic Mars missions. However, the future of the program is in serious doubt due to years of underinvestment. Though NASA is working on a new rover mission that will prepare Mars samples for return to the Earth, the lack of a comprehensive sample return strategy poses a challenge to continued U.S. leadership in Mars exploration in the coming decade, with repercussions that could undermine continued operations of surface missions in the 2020s and threaten the timeline of the first human mission to the Martian surface.

The scientific community identified a rover to begin sample return from Mars as the most important large-class mission for all of planetary science in this decade. The Planetary Society supports the goal of sample return that would provide the direction necessary to re-establish a comprehensive Mars Exploration Program strategy and plan for the 2020s. This would also ensure that NASA is able to advance its readiness for the human exploration of Mars in the 2030s.

The nation has reached a critical decision point regarding the Mars Exploration Program. We believe there are two reasonable pathways for the future of U.S. robotic exploration of Mars:

- Invest modest capital beginning in FY 2018 to maintain the scientific and technical capabilities that have taken decades to acquire while advancing the technological and surveying knowledge necessary for human exploration
- Maintain a minimal program that collects and prepares samples of Mars with the hope that, at some future date, another nation or entity will return them

The Planetary Society believes the first pathway is the correct choice for the nation and our international partners. In an effort to help NASA achieve these goals, The Planetary Society makes three recommendations:

1. NASA should immediately commit to a Mars telecommunications and high-resolution imaging orbiter to replace rapidly aging assets currently at Mars.
2. NASA should begin formulation of a sample retrieval rover and Mars Ascent Vehicle mission to continue the overall Mars Sample Return campaign.
3. NASA should formulate a follow-on strategy to the Robotic Mars Exploration Strategy, 2007-2016 document.

1. Introduction

Mars is a cousin of Earth, and exploring Mars provides extraordinary insights in understanding the origin and evolution of life, comparative climatology, and long-term human survival. Mars currently has a thin atmosphere and reservoirs of surface and subsurface water ice. Its surface is a frozen tundra bathed in radiation that is hostile to living organisms. But Mars was not always like this. Billions of years ago, Mars possessed rivers and freshwater lakes. The atmosphere was thicker, and the planet was warmer. Mars hosted a habitable environment at the very time life began on Earth. While life is unlikely to exist today on the surface, it could yet be discovered deep underground where it has access to water and is safe from surface radiation.

Because of the scientific richness of the planet and its relative accessibility—launches can occur every 2.2 years and reach the planet within 6- 8 months with current technology—NASA and other space agencies have sent dozens of robotic missions to explore Mars since the early 1960s. NASA formalized its ongoing commitment to lead the world in the exploration of the Red Planet in 2000 with the birth of its Mars Exploration Program (MEP), which has overseen the design and operations of seven successful robotic missions, and has plans to launch an eighth in 2020.[1]

Budget cuts to the Mars Exploration Program in 2009 and 2013 upset the planned mission cadence necessary for progress on the scientific goals outlined in its strategic plans.[2]

This report assesses the state of the MEP at NASA and looks at the future of the program through the early 2020s. As a new administration takes the reins at NASA and formulates the next steps in the MEP strategy, early decisions regarding the Mars program will have long-lasting repercussions for NASA's robotic and human presence at the Red Planet.

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[1] An additional robotic mission to Mars, InSight, will launch in 2018, but as part of NASA's Discovery program. InSight is a stationary lander which will provide geophysical measurements relating to the interior of Mars.

[2] Mars Advanced Planning Group, Robotic Mars Exploration Strategy, 2007-2016. Pasadena, CA: Jet Propulsion Laboratory, 2006. JPL 400-1276. Available at: https://mepag.jpl.nasa.gov/reports/3715_Mars_Expl_Strat_GPO.pdf

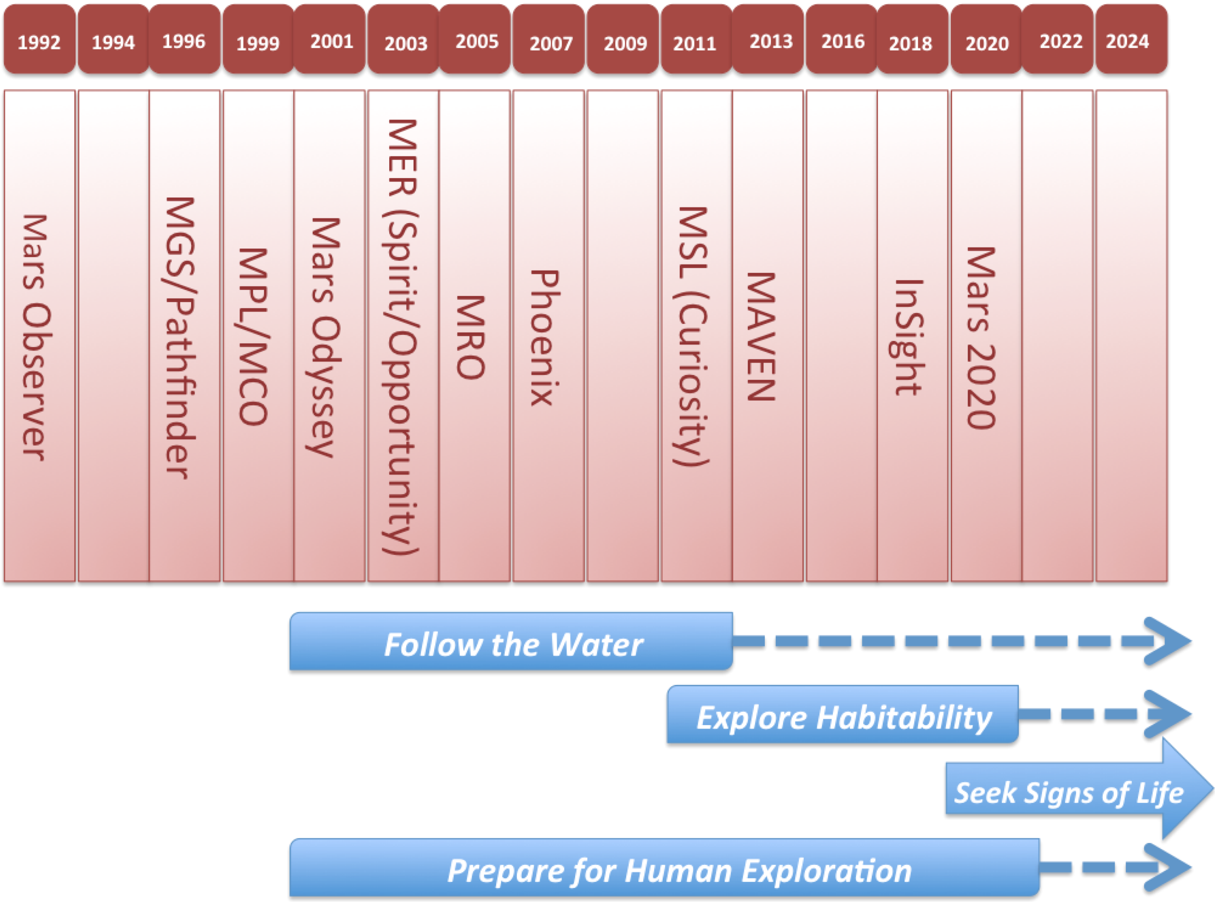

Figure 1. The evolving strategy for Mars exploration at NASA. Note that "Follow the Water" was announced in 2000 and did not drive the design or science goals of the Mars Global Surveyor or Mars Pathfinder missions that launched in 1996. Source: NASA.

2. The Mars Exploration Program

2.1 About the Program

After a 17-year hiatus that followed the Viking missions, NASA began a renewed effort to explore Mars in the 1990s. The first mission was Mars Observer, an orbiter that failed just days before it reached the planet in 1993. Pathfinder, a small lander and rover, had better luck, and successfully landed in 1997, reinvigorating scientific and public interest in the Red Planet. Mars Global Surveyor arrived at Mars that same year as part of the newly minted Mars Surveyor program. This initiative would have NASA send two missions to Mars at every launch opportunity under its "Faster, Better, Cheaper" strategy. However, failures of the Mars Polar Lander and Mars Climate Orbiter in 1999 led to an independent review board report[3] that found significant flaws in the Mars program as-implemented and recommended that NASA reorganize existing assets to create a centrally managed effort with programmatic oversight and budgetary responsibility for all of NASA's robotic Mars ambitions.

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[3] Mars Program Independent Assessment Team Report. March 14, 2000. Available at: https://ntrs.nasa.gov/search.jsp?R=20000032458

NASA Administrator Daniel Goldin tasked Scott Hubbard[4] with leading the development of a Mars program architecture addressing the issues identified in the Mars Program Independent Assessment Team Report as well as concerns of the White House, Congress, the National Academies, and the NASA Advisory Council, among others. NASA announced the reformulated Mars Exploration Program in October 2000 with Hubbard appointed as its first director.[5] The MEP Director is located at NASA Headquarters in Washington, D.C. NASA's Jet Propulsion Laboratory in California is the lead center for robotic Mars exploration and maintains a Mars Program Office that houses technical, management, scientific, and engineering staff to plan for continuity, interfaces, and dependencies between missions. The Director of the MEP currently reports to the Planetary Science Division Director at NASA's Science Mission Directorate.

At the initiation of the Mars Exploration Program, NASA announced plans for five missions spread out over 10 years, alternating between ground and orbiter missions at every Mars launch opportunity. These missions would share management and engineering expertise and incorporate new scientific and technical knowledge gained from each previous mission, gradually building experience and ultimately creating an unprecedented institutional capability for launching, orbiting, landing, and operating on Mars. NASA also created a competitive mission line—Mars Scout—that was modeled after the successful Discovery program and provided regular opportunities for the scientific community to propose mission concepts.[6]

The MEP maintains its own technology development program, provides research funding for Mars scientists, supports placement of U.S. scientific instrumentation on Mars missions led by international partners, conducts operations for all existing NASA Mars spacecraft, and engages in strategic planning for future missions, all while providing continuity of purpose and technological capability.

2.2 Current Mission Status

NASA currently has two rovers operating on the surface and three spacecraft operating in orbit at Mars (see Table 1), all of which are performing beyond their intended design lifetime. NASA also supports U.S. scientists on several science instrument teams on the European Space Agency's (ESA) Mars Express orbiter and a communications system on ESA's Trace Gas Orbiter (TGO).

NASA's ongoing missions are subject to an independent review process every 3 years, in which each mission team submits a new observation plan to a panel of outside experts who evaluate the proposed science against the ongoing costs of operation. In 2016, each

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[4] Scott Hubbard is retired from NASA and now serves on The Planetary Society's Board of Directors.

[5] NASA News Release, "NASA Outlines Mars Exploration Program for the Next Two Decades," October 26, 2000. Available at: https://www.nasa.gov/home/hqnews/2000/00-171.txt

[6] After just two missions, Phoenix and MAVEN, NASA discontinued the Mars Scout line, allowing small, PI-led Mars projects to compete with projects to other destinations in the Discovery program. InSight was then selected for the Discovery program.

Mission	**Type**	**Launch Date**	**Planned Mission Duration**	**Actual Mission Duration**	**Mission End**	**Approximate Annual Operating Cost**
Mars Odyssey	orbiter	4/7/2001	3 years	15.8 years	Ongoing	$12.7 million
MER Spirit	rover	6/10/2003	92 days	8 years	5/2011	N/A
MER Opportunity	rover	7/7/2003	92 days	13.6 years	Ongoing	$12.5 million
Mars Reconnaissance Orbiter	orbiter	8/12/2005	5 years	12.8 years	Ongoing	$28 million
Phoenix	stationary lander	8/4/2007	92 days	157 days	10/2008	N/A
MSL Curiosity	rover	11/26/2011	2 years	5.2 years	Ongoing	$57 million
MAVEN	orbiter	11/18/2013	2 years	3.2 years	Ongoing	$23.5 million
		Average	*1.8 years*	*10.2 years*		

Table 1. Missions launched and operated under NASA's Mars Exploration Program. Annual operating costs are sourced from the FY 2018 President's Budget Request.

Mars mission passed this review process and was approved for continued operations.[7]

NASA is currently in the implementation phase of the Mars 2020 rover project, a follow-up to the Curiosity rover, that is budgeted at $2.4 billion and planned to launch in July of 2020.[8]

2.3 Scientific Direction

The Mars Exploration Program derives its strategic goals from the scientific community. The primary guiding document is the Decadal Survey for Planetary Science prepared by the National Academy of Sciences, Engineering, and Medicine. The decadal surveys represent the consensus view of the scientific community for the top priority scientific goals in each of NASA's four space science divisions. The current Decadal Survey for Planetary Science, *Visions and Voyages*,[9] was released in 2011 and applies to the decade 2013-2022.

In addition to the Planetary Science Decadal Survey, NASA receives input through the Mars Exploration Program Analysis Group (MEPAG) that has a rotating chair and membership from the scientific community.[10] MEPAG provides information to NASA's Planetary Science

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[7] McCuiston, Doug, et. al. Report for Planetary Mission Senior Review 2016. June 17, 2016. https://solarsystem.nasa.gov/docs/PMSR2016_Report_Final.pdf.

[8] NASA Office of the Inspector General. NASA's Mars 2020 Project. January 30, 2017. https://oig.nasa.gov/audits/reports/FY17/IG-17-009.pdf

[9] Committee on the Planetary Science Decadal Survey, Space Studies Board, Division on Engineering and Physical Sciences, National Research Council. Vision and Voyages for Planetary Science in the Decade 2013-2022. Washington, D.C.: National Academies Press, 2012.

[10] Mars Exploration Program Analysis Group (MEPAG) website: https://mepag.jpl.nasa.gov

Division Director and contributes to NASA's Advisory Council, which formally advises the NASA Administrator.

MEPAG's four primary goals for Mars exploration[11] are to:

1. Determine if Mars ever supported life
2. Understand the processes and history of climate on Mars
3. Understand the origin and evolution of Mars as a geological system
4. Prepare for human exploration

2.4 Programmatic Direction

A dedicated Mars Exploration Program enables NASA to pursue ambitious exploration and science goals through systematic and strategic investment over the course of multiple missions. This strategy allows for a variety of landed and orbital assets to incorporate complementary scientific instruments in order to address overarching scientific questions. A coherent program strategy allows NASA to allocate its resources more efficiently, incorporates lessons and scientific discoveries from previous missions, and spreads the risks inherent in spaceflight over a number of missions, helping to ensure a return on public investment.

The program began with the "follow the water" principle, i.e., to characterize the ancient environment on the Red Planet to confirm if liquid water was present on the surface over long periods of time (see Figure 1).

NASA launched six Mars missions under this initial organizing principle and conclusively demonstrated the long-term presence of standing bodies of fresh and brackish water on the surface of Mars billions of years ago.

With the launch of the Mars Science Laboratory (MSL) Curiosity rover in 2011, the MEP entered a new phase of its organizational strategy: to "explore habitability," striving to understand the broad environmental and chemical context of ancient Mars and its ability to support life.

NASA is preparing the upcoming Mars 2020 rover to "seek signs of life," the next step in the MEP strategy. Though there is important in-situ science planned for Mars 2020, the rover is also designed to drill and cache stores of Martian surface samples for an as-yet-unapproved sample return campaign that will greatly aid the goal of seeking signs of ancient or extant life.

Running parallel to these scientific goals, the Mars Exploration Program serves to inform planning for future human exploration. NASA's robotic missions contribute to a future human mission to Mars by providing data on topics such as planetary protection issues, surface and in-transit radiation measurements; landing site characterization and mapping, entry, descent, and landing tests; dust conditions; and potential in-situ resource utilization (ISRU) identification and validation. The Human Exploration and Operations Mission Directorate (HEOMD) at NASA provided instrumentation onboard the Curiosity and Mars 2020 spacecraft to measure the conditions of landing on Mars. HEOMD also provides the upcoming Mars Oxygen ISRU Experiment (MOXIE) on the Mars 2020 rover.

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[11] MEPAG (2015), Mars Scientific Goals, Objectives, Investigations, and Priorities: 2015. V. Hamilton, ed., 74 p. white paper posted June, 2015 by the Mars Exploration Program Analysis Group (MEPAG) at: https://mepag.jpl.nasa.gov/reports.cfm

The Mars Reconnaissance Orbiter is actively coordinating with the human exploration program on an observation campaign to identify potential sites for future human exploration.[12]

2.5 Scientific Return

The scientific return from the Mars Exploration Program has been immense. As of 2016, Odyssey, Spirit & Opportunity, the Mars Reconnaissance Orbiter, and Curiosity have provided data for more than 2,300 peer-reviewed scientific articles.[13] No other planet besides Earth has been studied continuously in such detail.

Major discoveries include the confirmed presence of water on ancient Mars, that the planet was habitable for life as we know it, and that ice lurks beneath the surface in both the northern and southern regions. These discoveries provide an increased understanding for the processes by which Mars lost much of its atmosphere and major advances in knowledge of Mars' geologic history and processes. The program has also provided critical data relating to human exploration by measuring radiation levels in transit and on the surface by obtaining detailed information about the Martian atmosphere when landing and globally mapping potential resources for use by human explorers.

The parameters governing MEP missions are derived from the scientific questions prioritized in the decadal surveys. In the 2003 Decadal Survey, *New Frontiers*, the authoring committee proposed four cross-cutting themes consisting of 12 key scientific questions in planetary science, and three themes consisting of 10 key questions directly related to Mars science. The committee proposed four Mars Exploration Program missions addressing five of the 12 cross-cutting key questions and all 10 of the Mars science key questions. Those missions were:

- Mars Science Laboratory
- Mars Long-Lived Lander Network
- Mars Upper Atmosphere Orbiter
- Mars Sample Return

Additionally, the committee recommended the Mars Scout line as the top small-class priority for Mars exploration, which would fly missions at every Mars launch opportunity. The Mars Science Laboratory was the top medium-class priority for Mars, followed by the Mars Long-Lived Lander Network. The committee recommended that NASA begin planning for a Mars Sample Return mission as a large-class mission to take place in the 2013-2022 decade.

In the decade following publication of New Frontiers, NASA developed and launched the Mars Reconnaissance Orbiter (2005), the Mars Science Laboratory rover Curiosity (2011), and the first Mars Scout, Phoenix (2007). With additional data provided by the 2001 Mars Odyssey mission, the Mars Exploration Rovers Spirit and Opportunity (2003), as well as U.S. instruments aboard ESA's Mars Express (2003), these missions provided critical data addressing three of the 12 cross-cutting key scientific questions and all 10 of the Mars

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[12] Ben Bussey and Stephen Hoffman. Human Mars landing site and impacts on Mars surface operations. Presented at the IEEE Aerospace Conference, March 2016. DOI 10.1109/AERO.2016.7500775.

[13] Email from Richard Zurek, Chief Scientist for the Mars Program Office at the Jet Propulsion Laboratory, to Casey Dreier, Director of Space Policy for The Planetary Society, February 2, 2017.

science key questions in the New Frontiers survey. Budget constraints, shifting scientific priorities, and technical issues precluded a Mars Long-Lived Lander Network. In 2013, NASA launched the second (and final) Mars Scout mission, the Mars Atmosphere and Volatiles EvolutioN (MAVEN) orbiter. A key aspect of the science of the Mars Long-Lived Lander Network will be carried out by the 2018 InSight mission, which will be funded through the Discovery program.

2.6 Scientific and Technical Workforce

The United States has invested billions of dollars since 1996 to develop unprecedented institutional knowledge and capability for Mars exploration. NASA's Jet Propulsion Laboratory in California contains the primary government engineering and operations workforce for Mars orbital and rover missions, along with many on-site contractors. Lockheed Martin Space Systems near Denver, Colorado, has been the prime contractor for every orbiter in the Mars Exploration Program, as well as the Phoenix and InSight stationary landers.

From a technical point of view, the scientists, engineers, and technicians who build and operate Mars spacecraft possess skills unique to spaceflight and often require years of on-the-job training in addition to advanced education. In 50 years, the United States is the only nation to ever successfully land a spacecraft on Mars, and the Curiosity rover's landing via the Sky Crane technique in 2012 proved that NASA's technological capabilities are at the very leading edge globally. But a lack of missions to Mars will erode this unique community of technically experienced individuals as they move on to different challenges, either by choice or by lack of work. This creates a "brain drain" within the Mars engineering community as it loses irreplaceable institutional knowledge that must be re-built in the future. Skills will be lost that will certainly be needed given NASA's commitment to send humans to Mars in the 2030s. Lost NASA capabilities will also negatively impact the ambitions of SpaceX, which will depend on NASA's technological expertise to assist in its Red Dragon program of Mars missions planned in the 2020s (see Addendum for more information).

The individuals who constitute the scientific teams for robotic NASA missions often include NASA scientists, but the majority of the teams are comprised of independent researchers housed at institutions outside of the federal government such as universities and research institutes. The Mars scientific community that serves on these missions is therefore spread throughout the nation. Funding provided by the Mars Exploration Program supplements the salaries of the vast majority of Mars scientists (many of whom are guaranteed only partial salaries by their academic institutions) and enables them to pay postdoctoral researchers and graduate and undergraduate students, a critical part of the fabric of the Mars science community.

In addition to funding, these researchers depend on the data provided by NASA's robotic missions to conduct their work—data provided by almost no other sources. History demonstrates that if NASA does not regularly fly missions that provide data relevant to a particular field of scientific inquiry, the field begins to stagnate as scientists move to other research areas and fewer new students enter the field.

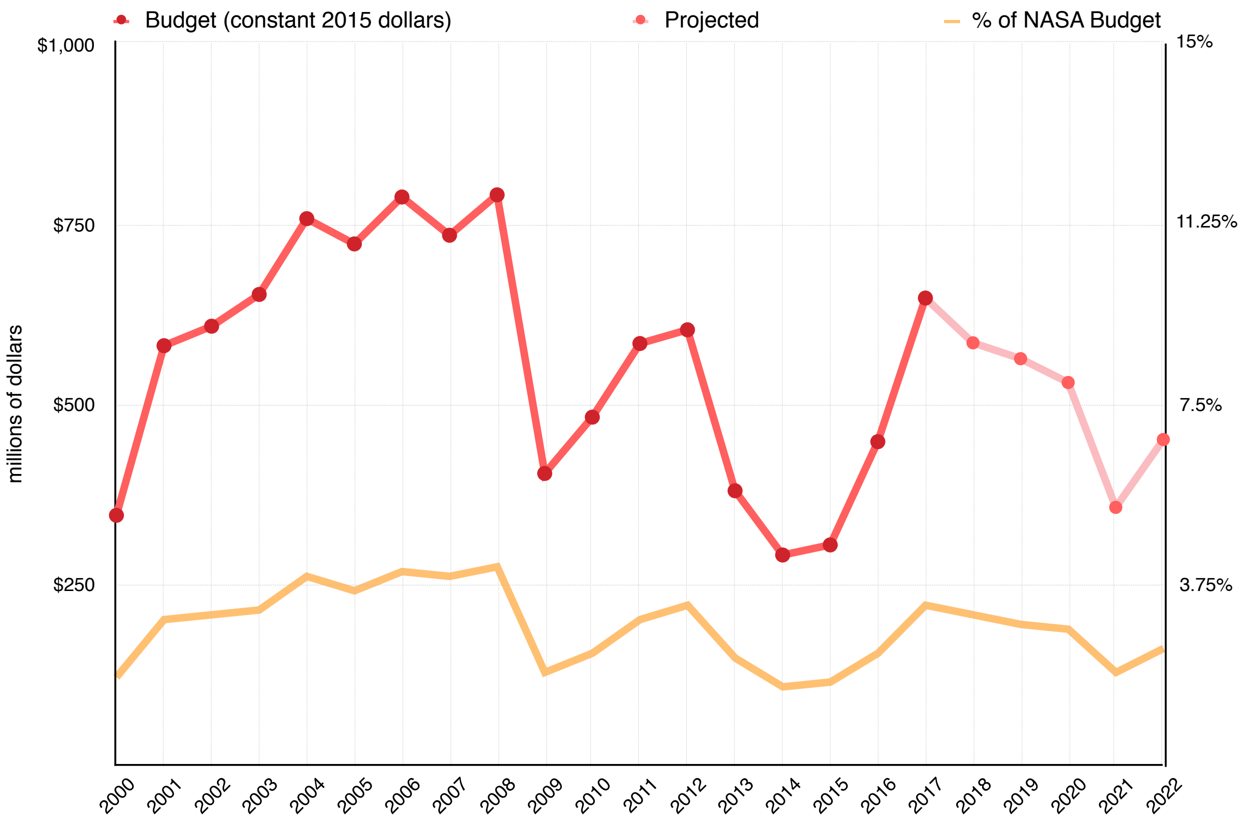

Figure 2. Left axis: the MEP budget, adjusted for inflation, since the start of the program. Right axis: the MEP as a percentage of NASA's total budget. Values from 2000 to 2016 are "actual" amounts spent, 2017 is the "enacted" amount, and values after 2017 are projections from the President's FY 2018 budget request. Note the two large cuts in FYs 2009 and 2013. These occurred after a cost overrun on the MSL mission in 2009 and as a consequence of the sequestration legislation in Congress and a decline of planetary science as a priority for NASA more generally.

2.7 Program Budget

The Mars Exploration Program is projected to receive $1.6 billion less in the 2010s than it did in its first decade (see Figure 2). During this same period, NASA shifted to expensive large-class missions to address scientific questions posed in the evolving Mars exploration strategy (see Figure 6) while shouldering the cost of operating its existing fleet of Mars spacecraft. The net effect has been the collapse of the development pipeline and the fewest number of new missions to Mars in a decade since the 1980s.

The Mars Exploration Program received $647 million in the FY 2017 final appropriations, accounting for approximately 35% of the budget of NASA's Planetary Science Division and 3% of NASA's total. After reaching a low point of $288 million in 2014, the program's budget has been on an upward trend and is projected to peak in 2018. This is primarily driven by development costs associated with the upcoming Mars 2020 rover mission. The projected decline after FY 2019 reflects the absence of any follow-on missions in the development pipeline. This instability is a marked difference from the program's budget in the 2000s, when it enjoyed an unusually

	2011	**2012**	**2013**	**2014**	**2015**	**2016**	**2017 (estimated)**	**2018 (projected)**
Operating Costs	$55.6	$136.2	$114.7	$142.1	$133.4	$126.1	$142.9	$136.5
MEP Budget	$547	$578	$370	$288	$305	$513	$647	$585
% of MEP	10.2%	23.6%	31.0%	49.3%	43.7%	24.6%	22.1%	23.3%

Table 2. Costs of operating Mars missions can account for a significant percentage of the MEP's total budget, making it difficult to provide resources needed to develop future missions. Dollar amounts in millions. Not adjusted for inflation. Source: NASA Budget Requests, FYs 2013 - 2018.

stable 5 years of funding, averaging $750 million annually (adjusted for inflation).

The Mars Exploration Program's budget issues led NASA to cancel the Mars Scout[14] program in 2010 and to pull out of a proposed joint rover mission and significantly reduce its contribution to an orbiter in ESA's ExoMars program in 2011. More fundamentally, this shifted NASA's Mars mission pipeline from a parallel process, in which multiple missions were in different stages of development at the same time, to a serialized process, in which new missions could only start after the conclusion of the previous mission (Figure 3). For example, the Mars 2020 rover was not announced until December of 2012—four months after the landing of Curiosity—and did not enter formulation until 2013, when MAVEN development was nearly finished. Due to the multi-year timelines for creating new missions, this had the impact of greatly diminishing the rate at which NASA could replace aging assets at Mars. No new Mars missions have been approved since 2013.

However, the Mars Exploration Program budget is used for more than just spacecraft development. It must shoulder ongoing costs to operate existing spacecraft including employment of teams of engineers and scientists to operate each spacecraft safely, costs for use of NASA's deep space communication system, and costs to assess the data returned to help plan meaningful scientific observations. This operational cost is budgeted in advance for the primary mission phase of a project, but not for extended periods beyond that. Although NASA includes funds for extended missions in its budget projections, planning can be difficult when every mission significantly outlasts its designed lifetime. These long lifetimes have been highly beneficial, however, as several major discoveries have been made after the prime mission.[15] In aggregate, the cost of operating five missions at Mars is non-trivial and can account for a significant percentage of the MEP's annual budget. In 2014, for example, NASA spent nearly 50% of the Mars program's budget on operations (see Table 2).

With no missions in development after Mars 2020, the budget for the Mars program will continue to decrease in the future as missions age and end.

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[14] Mars Scout was a competed mission line that enabled the scientific community to propose responsive, low-cost mission concepts that would fly every 4 years. The Phoenix lander and MAVEN orbiter were the only two Scout missions that ultimately flew.

[15] Committee on NASA Science Mission Extensions, Space Studies Board, Division on Engineering and Physical Sciences, The National Academies of Science, Engineering, and Medicine. Extending Science: *NASA's Space Science Mission Extensions and the Senior Review Process*. Washington, D.C.: The National Academies Press, 2016.

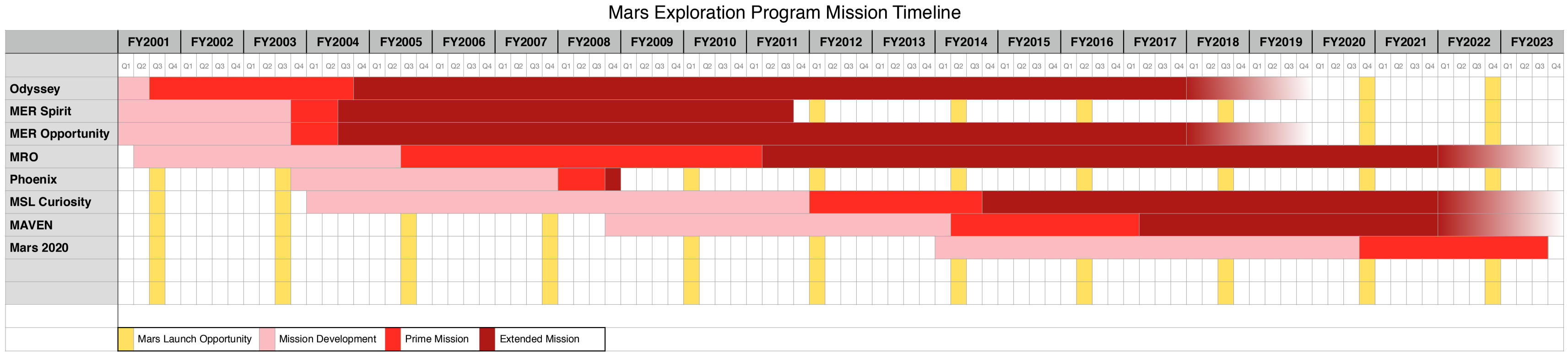

Figure 3. The Mars Exploration Program mission timeline, broken down by development time, prime mission operations (which includes launch and travel time), and extended mission operations. Earth-to-Mars launch opportunities occur approximately every 26 months and are highlighted in yellow.

Note that, in its second decade, the program moved from developing multiple Mars missions in parallel to developing single missions in series.

2.8 Communications Relay Infrastructure at Mars

NASA maintains a satellite communications network around Mars, the only other planet beyond Earth with this capability. NASA's orbiting science spacecraft serve as data relay satellites for ground missions by taking time off from observations to communicate with landed assets and send their data back to Earth (Figure 4).

Designing surface robots that depend on orbital assets provides several advantages. Orbiting spacecraft have larger and more powerful communications antennae and can transmit data back to Earth at far higher data rates. Surface missions can send large amounts of data to an orbiting spacecraft very quickly as it passes overhead, freeing up time for surface operations and scientific exploration. It also allows engineers to design small, low-power antennas for direct-to-Earth (DTE) communications on surface missions (or, in the case of the Phoenix lander, not including a DTE antenna at all). Limiting the mass and power requirements of surface craft provides significant cost savings due to lower launch vehicle lift requirements, reduced mass requirements for entry, descent, and landing, and increased mobility. It is only due to the presence of reliable data relay satellites around Mars that NASA is able to use scientific instruments that generate significant amounts of data while maintaining the mobility of its rovers.

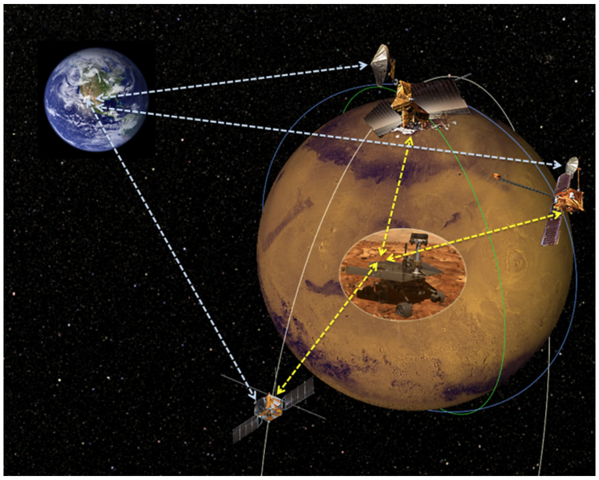

Figure 4. Orbiting spacecraft serve as a Martian satellite communications network for NASA's rovers and landers. Credit: NASA/JPL-Caltech.

Mars Odyssey and the Mars Reconnaissance Orbiter (MRO) act as the primary relay satellites for the Opportunity and Curiosity rovers, respectively. Each orbiter passes over each rover twice per sol (Martian day). They also provide critical communications coverage during entry, descent, and landing sequences for both NASA and European Space Agency (ESA) missions.

Maintaining this telecommunications infrastructure is an ongoing challenge for the Mars Exploration Program. Odyssey and MRO have been in deep space for 16 and 12 years, respectively. And while both are generally healthy, they are showing signs of age. A hardware failure in 2012 forced Odyssey to switch to a backup mechanism used to stabilize the spacecraft.[16] Should its backup fail, the spacecraft would exhaust its remaining fuel supplies within a year. MRO is in better shape, but has aging batteries and gimbals and is being carefully managed to allow operations to continue through 2023, barring any unexpected issues.

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[16] Orbiter Out of Precautionary 'Safe Mode'. NASA press release. June 12, 2012. https://www.jpl.nasa.gov/news/news.php?feature=3411

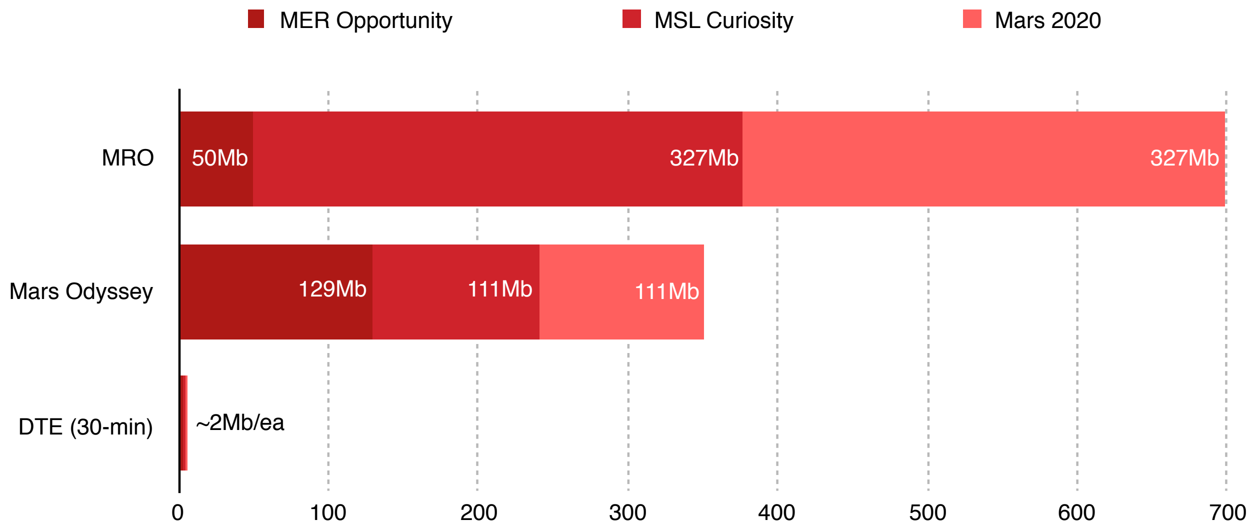

Figure 5. Comparing estimated daily data return (in megabits) from Mars orbiters vs. direct-to-Earth (DTE) communications. Note that the minimum data return for mission success of MSL Curiosity is 250Mb/sol. Mars 2020 rates will be similar but likely higher due to the large amount of data generated by its instrument suite. The DTE rates are rough estimates made for comparison purposes only. Numbers assume an average data rate of 1.1 kb/s per sol for each rover. Ground assets are able to communicate their data to the orbiters in brief bursts of about 15 minutes twice per sol. For a direct comparison we provide a DTE communications estimate using 30 minutes of transmission time. Source for MRO and Odyssey data: Edwards, et. al. *Replenishing the Mars Relay Network*, 2014 IEEE Aerospace Conference, March 2014.

NASA has invested in several backup options, though they are suboptimal replacements for its two primary relay satellites.

One backup is the Mars Atmosphere and Volatile EvolutioN (MAVEN) spacecraft, which has specialized hardware enabling it to serve as a data relay satellite. However, its science orbit is elongated and the spacecraft passes over the rovers only once per day, precessing in time. MAVEN could be repositioned into a more circular orbit, should it be needed, though it would greatly impact the science return of this mission. But even so, the precessing orbit would still make planning surface operations difficult.

The European Space Agency (ESA) maintains two orbiters at Mars, and both can serve as backup relay satellites. Mars Express, launched in 2004, demonstrated data relay capability for NASA's surface missions, albeit with a slower data rate than Odyssey or MRO. The Trace-Gas Orbiter (TGO) arrived at Mars in the Fall of 2016 and contains a NASA-provided antenna system, allowing it to communicate at high speeds with surface assets. Though TGO has the highest relay bandwidth capacity of any orbiter yet sent to Mars, both it and Mars Express are in orbits that precess through local time. Also, the top priority for TGO is to support ESA's upcoming ExoMars rover mission launching in 2020.

The Mars 2020 rover will launch in July 2020 and land in early 2021. Its prime mission is approximately 3 Earth years,[17] carrying it into 2024, and there is reasonable expectation for

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[17] Mars 2020 is "qualified" for a 1.5 martian-year prime mission. Matt Wallace, presentation to the Mars Exploration Program Advisory Group, Monrovia, CA, February 22, 2017. Presentation available at: https://mepag.jpl.nasa.gov/meeting/2017-03/06.2%20MW%20-%20Project%20Overview%20-%20MEPAG.pptx

an extended mission beyond that. At that point, MRO will be nearly 20 years old and likely the only data relay satellite available that could support rover operations planning. Even if MRO continues through the prime mission of Mars 2020, it is unlikely to last through the remainder of the decade of the 2020s, leaving a potential gap in NASA's telecommunications infrastructure for future surface missions at Mars, including potential extended missions for Mars 2020. Curiosity—Mars 2020's sister rover—also had a 2-year primary mission and is now in its fifth year of surface operations.

Additionally, the scientific instrument suite on Mars 2020 will generate more data than any landed mission in history,[18] and it will require a reliable data relay system to ensure the primary mission goals are met. While Mars 2020 does have the means to communicate directly with Earth, depending on a direct-to-Earth (DTE) link reduces data speed from megabits (millions of bits) per second to roughly one kilobit (thousands of bits) per second (see Figure 5). This three-orders-of-magnitude data rate difference has been likened to switching from high-speed broadband to a dial-up modem for internet access.[19] The lack of a functioning data relay satellite would threaten the mission success of NASA's flagship Mars rover and potential future landed missions in the 2020s.

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[18] Edwards et. al. *Replenishing the Mars Relay Network*, IEEE Aerospace Conference, March 2014. DOI: 10.1109/AERO.2014.6836354.

[19] Email with Dr. Chad Edwards, JPL. April 2017.

3. The Future of the Mars Exploration Program

In the 2011 Decadal Survey report, *Visions and Voyages*, the report committee proposed three cross-cutting themes consisting of 10 key scientific questions in planetary science and three themes consisting of seven key questions directly related to Mars science.[20] The committee recommended a single Mars Exploration Program mission that would address six of the 10 cross-cutting key questions and all seven of the Mars science key questions: Mars Sample Return.

In response, NASA began planning for the Mars 2020 mission in 2012 based largely on technology developed for the Mars Science Laboratory project and capable of caching samples for recovery by a later mission.[21] Mars 2020 is the only Mars mission approved in the context of the current Decadal Survey and the only mission in development by the MEP.

But from the moment Mars 2020 lands on the Martian surface, a clock will be ticking. The

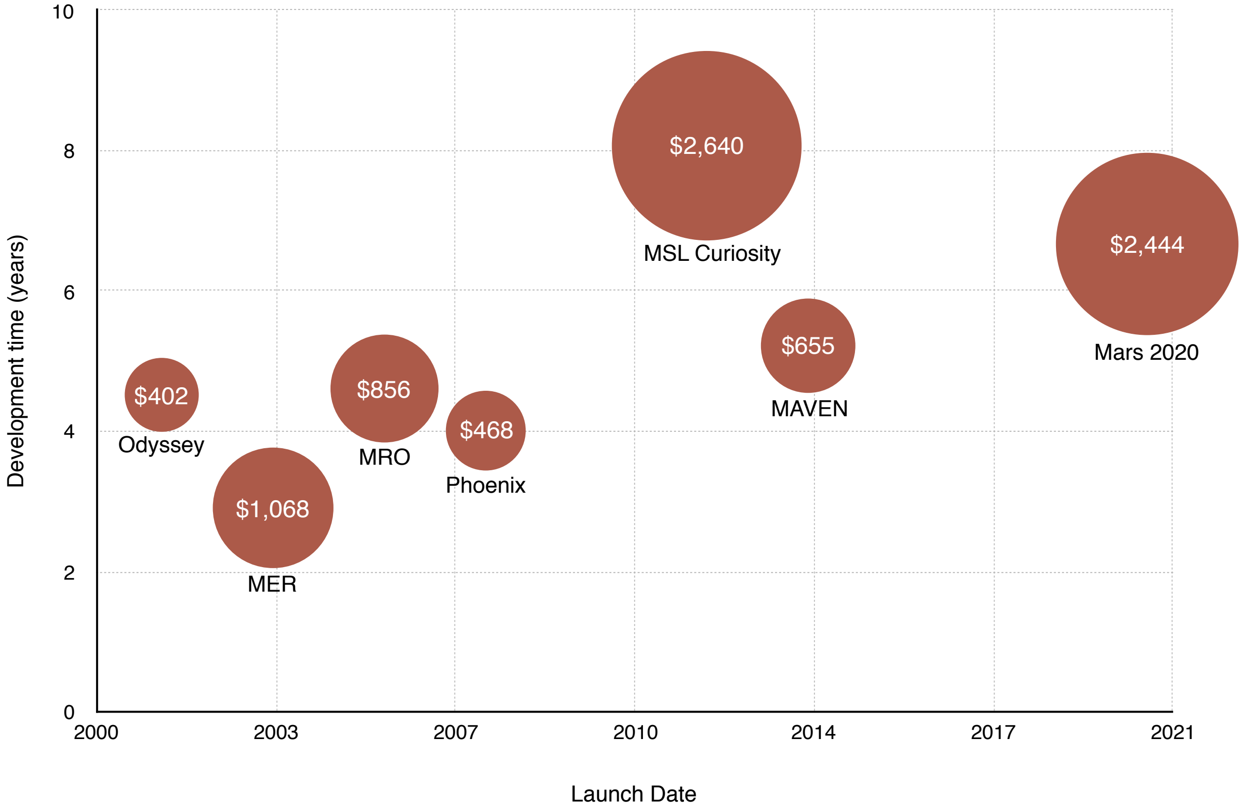

Figure 6. Development time (vertical axis) and overall costs (circular areas—dollars in millions, adjusted for inflation) of NASA's Mars missions have increased over time. As the overall budget for Mars exploration has diminished, this growth has placed extraordinary pressures on the program and limited the cadence of new missions.

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[20] Committee on the Planetary Science Decadal Survey, *Vision and Voyages for Planetary Science in the Decades 2013-2022*. Pp. 19, 137-174.

[21] The decadal committee said that the MAX-C Mars rover, the proposed U.S. part of a joint program with the European Space Agency's ExoMars program, would serve as the first of three missions to return samples from the planet's surface. The committee also stated that the U.S. contribution to the mission should be reduced from an estimated $3.5 billion to less than $2.5 billion. NASA withdrew from the joint program with ESA in 2011, declining to launch a Trace Gas Orbiter with U. S. instruments or a NASA rover in tandem with the ExoMars rover.

Mars 2020 rover uses a radioisotope power source—similar to the one on the Curiosity rover—that is capable of providing the rover with heat and electricity for at least 6 years, well beyond the 3-year primary surface operations currently planned. As described in the section above, the only orbiting spacecraft at Mars expected to be operational after 2020 is MRO, and it likely will not function after 2023. Without a new telecommunications and high-resolution imager at Mars by 2023, the Mars 2020 rover will operate with significantly restricted communications, drastically impacting the science return that will be received after a significant investment.

Further, there is crucial advantage to having a telecommunications and high-resolution imaging orbiter and a Mars Ascent Vehicle (MAV) mission operational at the same time. It certainly is not possible, for example, to fly the orbiter first, and have its operations end before the MAV mission occurs. So, in order to collect and return useful samples, NASA has a limited number of Mars launch opportunities—which occur only every 26 months—after Mars 2020 to send a telecommunications mission and a mission to retrieve the samples so that the two missions overlap sufficiently to realize the required capability dependencies.

Another consideration is that the sample containers on Mars 2020 have a finite lifetime. Current design specifications enable the preservation of scientifically valid samples for 20 years, though it is possible they could safely contain samples for a longer period.[22]

In *Visions and Voyages*, the committee evaluated three mission concepts for completing the goal of Mars sample return; a mission called MAX-C that eventually evolved into the Mars 2020 mission, a Mars Sample Return Lander with Mars Ascent Vehicle (MAV), and a Mars Sample Return Orbiter with Earth Entry Vehicle (EEV). The MAV lander would be equipped with a "fetch rover" to collect the samples cached by the Mars 2020 mission and place them in a rocket that would launch them to Mars orbit. The orbiter would then retrieve the samples and deliver them back to Earth. An independent cost review found that the lander mission including the first launch from the surface of Mars would cost approximately $4 billion, while the orbiter estimate was roughly $2.1 billion. Further studies have indicated that the missions could be accomplished for less,[23] though NASA has not begun formulation of either mission.

With only one mission in development, an average mission development time of approximately 5 years, and a launch window that opens every 26 months, NASA, the White House, and Congress must make decisions within the next fiscal year to ensure communications relay capability supporting ground operations of the 2020 rover and sample retrieval.

NASA is studying a number of concepts for its next orbiter, but it has not yet committed to flying a mission. Because of the timing of the Mars launch opportunities and the development time for spacecraft, NASA would have to commit to a new mission in its FY

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[22] According to the Mars 2020 project, the samples are "built to last 20 years but with no known failure mechanism known for longer durations," though the impact of the scientific integrity of the samples beyond that period is unknown. Email correspondence with Mars 2020 engineer Yulia Goreva, April 12, 2017.

[23] Jim Watzin, presentation to the Committee on Astrobiology and Planetary Science of the Space Studies Board, Space Science Week 2017, Washington, D.C., March 28, 2017.

2018 budget in order to realistically be ready for the 2022 Mars launch opportunity. And even then, the orbiter would arrive at Mars at the end of the prime mission of the Mars 2020 rover.

The United States is not the only nation planning to return samples from the Martian system. Russia last attempted to return samples from the Martian moon Phobos in 2012, though its spacecraft failed to reach Mars. Japan will make an attempt at sample return from the moons Phobos and Deimos in 2027,[24] while China has stated it intends to return samples from Mars in the 2030s.[25]

3.1 Recommendations

The Planetary Society makes three core recommendations:

1. NASA should immediately commit to a Mars telecommunications and high-resolution imaging orbiter to replace rapidly aging assets currently at Mars.
2. NASA should enter formulation for a sample retrieval rover and Mars Ascent Vehicle mission to continue the overall Mars Sample Return campaign.
3. NASA should formulate a follow-on strategy to the Robotic Mars Exploration Strategy, 2007-2016 document.

Recommendations 1 and 2 will ensure that NASA meets the highest priority Decadal Survey goal of returning samples from Mars. Recommendation 3 will help NASA to continue—and to capitalize on—the enormous success of the Mars Exploration Program by ensuring its Mars missions are strategically aligned to answer the most pressing science questions.

While The Planetary Society would certainly prefer that there are science instruments aboard the missions described in recommendations 1 and 2, in the absence of increased funding for the missions, the Society concurs with the Planetary Science Decadal Survey that returning samples from Mars is the highest science priority for the red planet. MSR cannot occur without the two missions outlined above.

To that end, we put forward two options for how to implement recommendations 1 and 2. The first option described below is consistent with NASA's previous commitment to Mars exploration and sets the agency on a firm path toward successful return of samples from the Martian surface while addressing other significant science questions. However, the necessary inclusion of new technology development for the orbiter could put a continuous high-speed telecommunications capability to and from the Martian surface in jeopardy for a time. The second option also keeps NASA on a path toward sample return, but on a slower trajectory and with fewer science returns, though it does result in continuous high-speed surface communications. We also put forward a third option as a contrast, which would effectively end the robotic Mars program.

Note that a high-resolution imaging camera is not required for continuing NASA's telecommunications relay capability to and

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[24] Hirdy Miyamoto. University of Tokyo. *Japanese mission of the two moons of Mars with sample return from Phobos.* Presentation to the MEPAG, March 2016. Available at: http://mepag.nasa.gov/meeting/2016-03/17_Miyamoto.pdf

[25] The State Council Information Office of the People's Republic of China, *China's Space Activities in 2016*, December 2016. Available at: http://www.scio.gov.cn/zfbps/32832/Document/1537024/1537024.htm

from the Martian surface, but it is required to map a landing site adequately in order to execute precision landing for a future Mars Ascent Vehicle mission, or other robotic or human landing needs. NASA has identified high-precision landing capability as critical to Mars sample return because it enables a minimal traverse for a fetch rover to acquire sample canisters prepared by the Mars 2020 rover.[26] A high-resolution imaging capability also aids investigation of the science goals put forth in the Decadal Survey, following on the performance of MRO's HiRISE camera that has produced images of two percent of the surface of Mars at the instrument's nominal resolution to date. The capability will also be vital to determining landing sites and the location of in-situ resources for any future human mission to the surface.[27]

Note that the budget charts below are based on publicly available information from NASA but also include analysis conducted by The Planetary Society. The cost models for a Mars Ascent Vehicle project and a Mars Telecommunications and High-resolution Imaging Orbiter are premised on various cost assessments in the Decadal Survey, data contained in NASA presentations, and ideal cost curves constructed from historical data. As a result, the annual dollar figures are subject to change due to factors such as cost phasing, project re-scopes, or international contributions. The figures are intended to provide a sense of the budgetary requirements for enacting each option.

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[26] Jim Watzin, presentation to the Committee on Astrobiology and Planetary Science of the Space Studies Board, Space Science Week 2017, Washington, D.C., March 28, 2017.

[27] MEPAG NEX-SAG Report (2015), *Report from the Next Orbiter Science Analysis Group (NEX-SAG)*, Chaired by B. Campbell and R. Zurek, 77 pages posted December, 2015 by the Mars Exploration Program Analysis Group (MEPAG) at: https://mepag.jpl.nasa.gov/reports/NEX-SAG_draft_v29_FINAL.pdf

3.2 Option 1 - Sample Return and Science in the 2020s

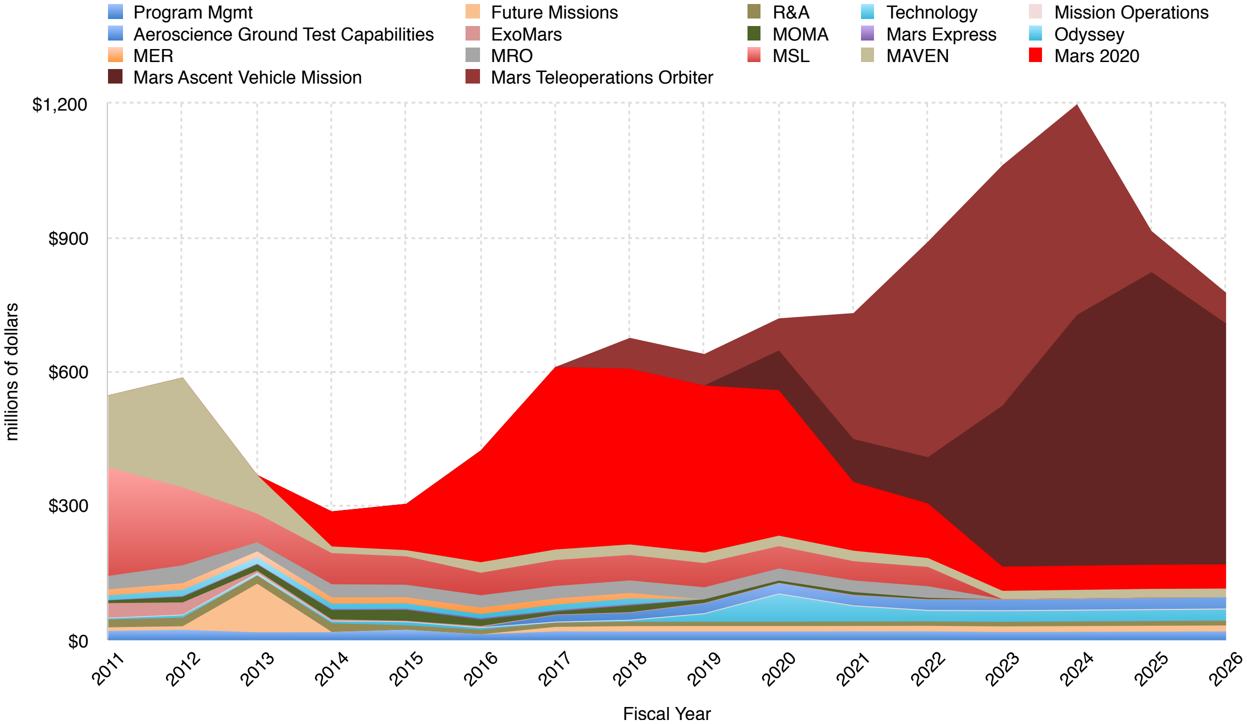

Figure 7. Option 1: MEP budget projections through 2026 including: a Mars telecommunications and imaging orbiter with a launch date of 2024 and a life cycle cost of $1.5 billion; A sample handling facility with a cost of $500 million; A Mars Ascent Vehicle mission with a launch date of 2026 and a life cycle cost of $2.5 billion.

Recommendation 1a. NASA should begin work on a large-scale project for the second (landed) stage of Mars Sample Return including a science package addressing key science questions outlined in the Decadal Survey. The formulation phase should include early technology development work in order to increase the Technology Readiness Level (TRL)[28] of an ascent capability to TRL-6 by the beginning of the next decadal survey period beginning in 2023. Initial costs for a typical large-class mission with a life cycle cost of $2.5 billion[29] are generally $80-$90 million per year for the first 2 years of formulation, though these annual costs could reasonably be reduced if the formulation schedule was extended by beginning work early.

Recommendation 1b. NASA should begin formulation of a Mars telecommunications and science orbiter with an Earth return vehicle immediately in order to meet the 2024 Mars launch window and begin construction of a sample storage and curation facility. Solar Electric Propulsion should be considered for this mission to enable Earth return and

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[28] According to the NASA website, "Technology Readiness Levels (TRL) are a type of measurement system used to assess the maturity level of a particular technology. Each technology project is evaluated against the parameters for each technology level and is then assigned a TRL rating based on the projects progress. There are nine technology readiness levels. TRL 1 is the lowest and TRL 9 is the highest." See: https://www.nasa.gov/directorates/heo/scan/engineering/technology/txt_accordion1.html

[29] Committee on the Planetary Science Decadal Survey, Vision and Voyages for Planetary Science in the Decades 2013-2022, Appendix C. All costs in this option assume that NASA can reduce the LCCs to the initial project estimates provided to the committee, rather than the CATE estimates of $2.1 billion for the orbiter and $4 billion for the lander.

demonstrate technology necessary for future cargo missions to support the human exploration of Mars. While the 2022 launch window would be preferable to 2024, it may not be technically feasible to meet a 2022 window given the added technology development inherent in an orbiter with the capabilities outlined here. The orbiter will allow NASA to maintain continuous telecom and high-resolution imaging capability at Mars to assist landed assets, particularly Mars 2020 and the follow-on sample recovery and launch mission. It will also provide data to address key scientific questions identified in the Decadal Survey. Initial costs for a typical large-class with a life cycle cost of $1.5 billion are generally $60-70 million per year for the first 2 years of formulation (see Figure 7).

3.3 Option 2 - Focused Sample Return in the 2030s

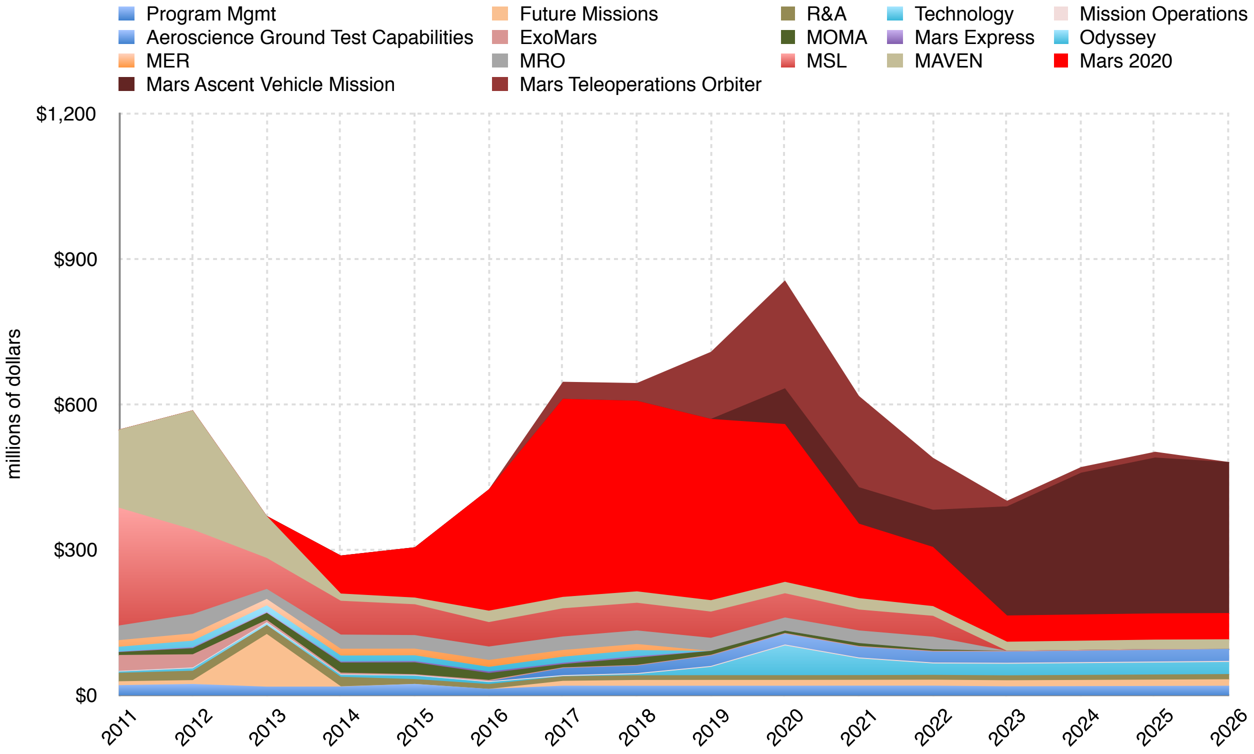

Figure 8. Option 2. MEP budget projections through 2026 including: a Mars telecommunications and imaging orbiter with a launch date of 2022 and a life cycle cost of $700 million; A Mars Ascent Vehicle mission with a launch date of 2026 and a life cycle cost of $1.5 billion.

Recommendation 2a. NASA should begin work on a project for the second stage of Mars Sample Return that (a) aims to de-scope the cost of the mission to $1.5 billion, even if this limits the inclusion of U.S. science instruments, and (b) includes early technology development work in order to achieve TRL-6 for a Mars ascent capability by the early part of the next decadal survey period beginning in 2023. Initial costs for a typical large-class mission with a life cycle cost of $1.5 billion[30] are generally $60-$70 million per year for the first 2 years of formulation, though these annual costs could reasonably be reduced if the formulation schedule was extended by beginning work early.

Recommendation 2b. NASA should begin a Mars telecommunications and science orbiter immediately in order to meet the 2022 Mars launch window. The 2022 launch window is preferable to the 2024 window as it ensures continuous telecommunications with assets on the Martian surface. The orbiter will allow NASA to maintain continuous telecom and high-resolution imaging capability at Mars to assist landed assets, particularly Mars 2020 and the follow-on sample recovery and launch mission. It will also provide data to address key

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[30] Watzin, James. "MEP Status and Future Planning." Presentation to the Committee on Astrobiology and Planetary Science, Washington, D.C., March 28, 2017. The LCC cited here assumes cost savings from using paraffin-based propellant for the MAV, eliminating the need for use of a radioisotope thermal-electric generator, as discussed in the presentation.

scientific questions identified in the Decadal Survey. Initial costs for a typical medium-class orbital mission with a life cycle cost of $700 million[31] are generally $30-40 million per year for the first 2 years of formulation, though these costs may be higher to meet a 2022 launch window (see Figure 8).

This option pushes the costs of developing and launching the Earth-return portion of the MSR mission into the future, but that mission would still be required in the 2030s. This option also defers (or shifts to other programs) the cost of establishing a dedicated Mars sample storage and curation facility on Earth.

Recent meetings of MEPAG's Mars International Collaboration Science Analysis Group[32] included discussions of international partner contributions of science instruments to a reduced-cost U.S. telecommunications orbiter. While such a strategy would aid NASA in meeting its goal of engaging in international collaboration, this should be pursued only if the funding for U. S. science instruments (other than the required camera) is not available (Option 2). In Option 3 even accommodation funds should be excluded to focus on the technology developments.

This option pushes the costs of developing and launching both the Mars ascent vehicle and Earth-return portions of the MSR mission into the future, but the MAV mission would still be required in the 2020s and the Earth-return mission no later than the early 2030s. This option also defers the cost of establishing a dedicated Mars sample storage and curation facility on Earth.

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[31] This LCC is derived from the cost of the Mars Reconnaissance Orbiter that had similar capabilities to the proposed telecommunications and high-resolution imaging mission.

[32] MEPAG MIC-SAG Report (2017), *Report from the Mars International Collaboration Science Analysis Group (MIC-SAG)*, Chaired by B. Jakosky, 33 slides posted March, 2017 by the Mars Exploration Program Analysis Group (MEPAG) at: https://mepag.jpl.nasa.gov/reports/MICSAG_slides_v16_FINAL.pdf

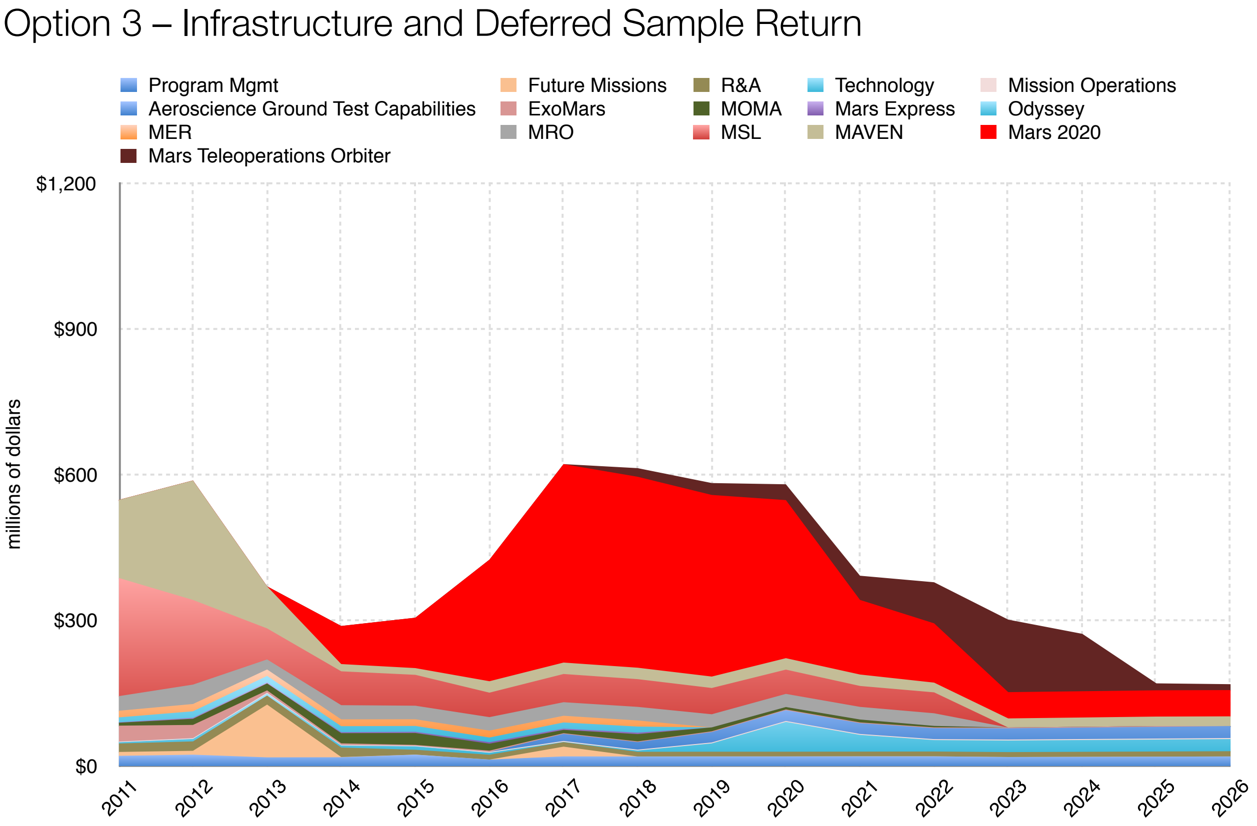
Option 3 – Infrastructure and Deferred Sample Return

Figure 9. Option 3. MEP budget projections through 2026 including: a Mars telecommunications and imaging orbiter with a launch date of 2024 and a life cycle cost of $450 million; ongoing technology studies into sample return.

Recommendation 3a. NASA should release plans for work on the second phase of Mars Sample Return, as outlined in Visions and Voyages. The plan should address the scope of the mission, including the schedule, size, and cost categories of the spacecraft in order to accomplish the mission within 10 years of the launch of Mars 2020. NASA should also continue work on Mars ascent vehicle technology in an effort to bring a concept to TRL-6 by the early part of the next decadal survey period beginning in 2023.

Recommendation 3b. NASA should begin a Mars telecommunications orbiter in order to meet the 2024 Mars launch window. The orbiter will allow NASA to maintain or reacquire telecom and high-resolution imaging capability at Mars to assist landed assets, particularly Mars 2020 (if it is still operational) and the follow-on sample recovery and launch mission. The cost of the orbiter should be limited to that of the necessary communications and high-resolution imaging capability. That is, communications and imaging capability should take priority over science on this mission. Initial costs for a typical small-class mission with a life cycle cost of $450 million are generally $15-20 million per year for the first 2 years of formulation (see Figure 9).

Recent meetings of MEPAG's Mars International Collaboration Science Analysis Group included discussions of international partner contributions of science instruments to a reduced-cost U.S. telecommunications orbiter. While such a strategy would aid NASA in meeting its goal of engaging in international collaboration, this should be pursued only if the funding for U. S. science instruments (other than the required camera) is not available (Option 2). In Option 3 even accommodation funds should be excluded to focus on the technology developments.

This option pushes the costs of developing and launching both the Mars ascent vehicle and Earth-return portions of the MSR mission into the future, but the MAV mission would still be required in the 2020s and the Earth-return mission no later than the early 2030s. This option also defers the cost of establishing a dedicated Mars sample storage and curation facility on Earth.

3.4 Risks

Development of the Mars Ascent Vehicle (MAV) technology is critical for the second Mars Sample Return mission, yet historically such technology development programs can be difficult to maintain when not attached to a specific project. Presentations to the National Academies of Sciences, Engineering, and Medicine committee examining the role of large-scale projects at NASA indicate that significant technology development in the Planetary Science Division occurs within large-scale projects.[33] The Juno and OSIRIS-REx missions have demonstrated that significant technology development can occur within medium-class missions as well. The risk of continuing MAV development outside of a project is that the pace of development could lag, leading to increased costs later when the technology is needed or even to cancellation if budgets become overly constrained.

If a Mars telecommunications orbiter mission is delayed to 2024 or later, NASA will likely incur a gap in its communication and imaging capabilities at Mars during potentially crucial stages of sample gathering by Mars 2020. If NASA does not replace communications and high-resolution imaging capabilities at Mars, surface operations would become more complex and rely on sub-optimal orbits of MAVEN and a non-NASA mission. NASA would effectively be abandoning more than 50 years of exploration at Mars, and the final stage of the current Mars Exploration Program strategy would be left unrealized after two decades of effort.

Budget and budget stability is also a risk. The necessary MEP program budgets for the three options are plotted compared to the FY18 President's Budget Request for the fiscal years 2018 - 2022. NASA's overall funding is currently projected to stay flat over this period, as is the overall funding for the Planetary Science Division that houses the Mars Exploration Program. NASA will be hitting peak development costs for a number of new planetary missions in the early 2020s as well. At the time of publication, the notional budget for the MEP only allows a basic telecommunications orbiter and deferred planning for a potential sample return campaign in the 2030s.

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[33] Committee on Large Strategic NASA Science Missions: Science Value and Role in a Balanced Portfolio, National Academy of Sciences, Engineering, and Medicine. Meetings held October 5-6, 2016 in Washington, D.C. Presentations available at: http://sites.nationalacademies.org/SSB/CurrentProjects/SSB_173492#presentations

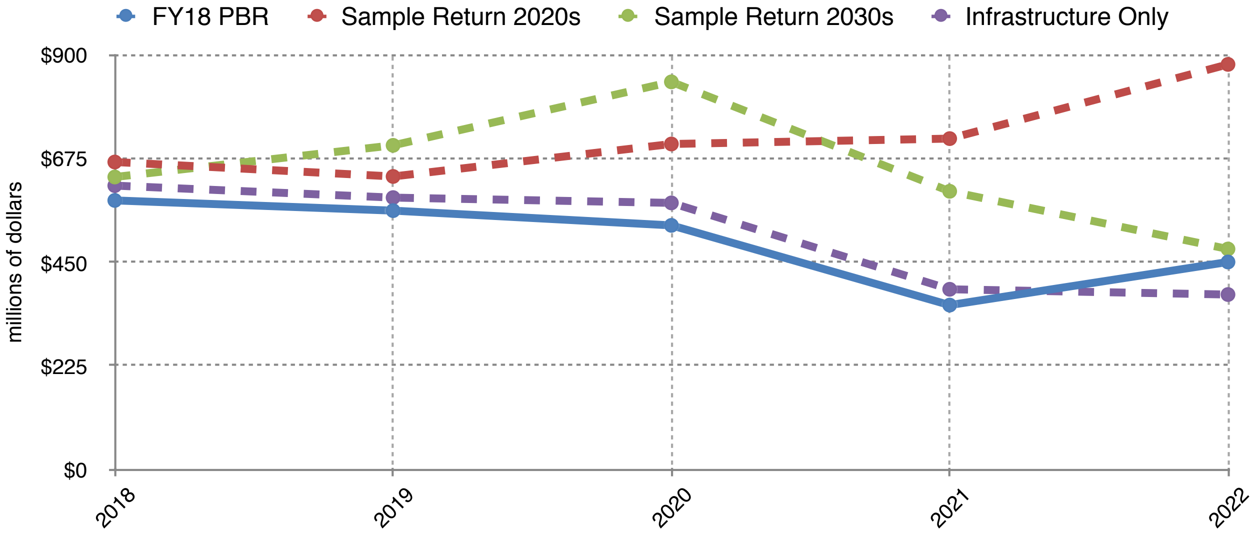

Figure 10. Comparing the annual Mars Exploration Program budget necessary to accommodate the Mars Exploration Program options as outlined in this paper to the actual notional budget for the program as proposed within the White House's FY 2018 budget request. Current budget projections most closely match the "infrastructure and deferred sample return" option.

4. Conclusions

At this moment, future planning for the Mars Exploration Program is rapidly moving away from the strategies that have served NASA, the United States, and the global scientific community so well in the past. Instead of a series of scientifically linked missions in various stages of development, NASA is working on a single flagship mission. And while this mission takes the first step to return samples to the Earth, NASA has yet to commit to follow-on missions to retrieve them or to address issues related to the long-term reliability of its telecommunications relay infrastructure.

NASA's existing Mars spacecraft are, on average, a decade old and operating years beyond intended design lives. As these existing missions inevitably end, there will be few new missions ready to replace the loss in scientific capability, to provide critical telecommunications relays for ground missions, or to scout ahead for human exploration. This situation is not quickly remedied. On average, it takes NASA 5 years to ready a Mars orbiter mission for launch (see Table 3), though development time increases with mission complexity. Launches themselves can occur only during brief alignments of Mars and Earth orbits that happen every 26 months. And new missions must be initiated through a Presidential budget request and approved by Congress in a process that can take upwards of a year to complete. To continue a healthy Mars program in the 2020s, NASA must take steps now (in the FY 2018 budget) to mitigate the long-term consequences of its current direction.

As outlined in *Visions and Voyages*, Mars sample return is the highest priority large scientific mission for the planetary science community. The planetary science decadal survey committee viewed sample return as a three-part mission (collect, launch, return) requiring continued orbital communications relay capability. The first component of sample return, Mars 2020, is currently in development, but a decrease in the overall budget for the MEP has precluded work on any follow-on missions to Mars.

NASA's orbital communication assets at Mars are far beyond their expected operational lifetimes and are not reliable assets into the 2020s. Newer spacecraft such as NASA's MAVEN and ESA's Trace Gas Orbiter can serve as communications relays in limited circumstances, but their science orbits and mission goals do not allow them to perform this function adequately. A dedicated new orbiter is necessary, but the lack of a firm commitment may already have delayed a potential replacement to 2024—after the prime mission of the Mars 2020 rover has been completed.

Sample return represents the culmination of a two-decade strategy for the Mars Exploration Program and four decades of consistent recommendations from the National Academies of Science, Engineering, and Medicine, but there are still many unanswered scientific questions for Mars identified in the Decadal Survey, particularly involving the evolution of the Martian geology and climate. Continued robotic exploration at Mars will also be critical for sending humans to the Red Planet and its moons. Orbiting spacecraft are the only means by which NASA can collect high-resolution images of the surface and evaluate potential landing sites. Robotic missions provide important data characterizing atmospheric conditions and performance behavior that can be applied to human missions. The Mars 2020 rover will carry an experiment to demonstrate the feasibility of in-situ resource utilization by generating oxygen from the Martian atmosphere—a critical capability needed to support human life on the surface.

Due to the long lead times of developing spacecraft and returning data, the consequences of policy decisions regarding budget and programmatic priorities commonly take years to become apparent. The cuts to the Mars Exploration Program in 2009 and 2013 disrupted the mission pipeline of the program, leading to a point where a single mission represents the entire future of the Mars program. In order to have a successful Mars program in the 2020s, NASA must make investments now.

Addendum: Mars Exploration and Private Industry Partners

NASA could partner with private industry to provide entry, descent, and landing (EDL) services for its sample return missions and/or orbital telecommunications services at Mars. To date, only SpaceX has announced plans to send a privately developed spacecraft to Mars, though the company has released limited information about the project publicly. NASA intends to provide instruments to collect data during EDL of SpaceX's first Red Dragon landing attempts in 2020 but, at the time of this writing, has not announced plans to include any other science instruments.[34] NASA also conducted a study in 2016 of industry partners' capabilities for potential telecommunications assets at Mars[35] and found that several companies possessed the ability to provide services, but "all required some combination of NASA funding for launch, an early deposit, and a guaranteed subscription [or] lease arrangement to recoup cost and ensure positive [return on investment]."[36] Should SpaceX or another firm develop capabilities necessary for parts of the sample return mission in time to contribute, or should NASA be able to establish an equitable plan with an industry partner for telecommunications services at Mars, then NASA management should evaluate possible collaboration with industry partners to acquire the needed services instead of contracting for construction of a vehicle.

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[34] Jeff Foust, "NASA exploring additional cooperation with SpaceX's Red Dragon mission," Space News, June 9, 2016. Available at: http://spacenews.com/nasa-exploring-additional-cooperation-with-spacexs-red-dragon-mission/

[35] NASA press release. "NASA Selects Five Mars Orbiter Concept Studies." July 18, 2016. Available at: https://www.nasa.gov/press-release/nasa-selects-five-mars-orbiter-concept-studies or http://images.spaceref.com/news/2016/NeMOIndustryDay.pdf

[36] Watzin, James. "Mars Exploration Program Update." Virtual presentation to the Mars Exploration Program Analysis Group, October 6, 2016.

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