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NASA's Planetary Science Portfolio

September 16, 2020

Report No. IG-20-023

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RESULTS IN BRIEF

NASA's Planetary Science Portfolio

September 16, 2020 IG-20-023 (A-19-013-00)

WHY WE PERFORMED THIS AUDIT

NASA's Planetary Science Division (PSD) is responsible for a portfolio of spacecraft, including orbiters, landers, rovers, and probes, that seek to advance our understanding of the solar system by exploring the Earth's Moon, other planets and their moons, asteroids and comets, and the icy bodies beyond Pluto. Currently, the planetary science portfolio consists of 30 space flight missions in various stages of operation. PSD missions fall under three categories: Discovery (small-class missions with development costs capped at $500 million); New Frontiers (medium-class missions with estimated development costs under $1 billion); and Flagship (large-class missions costing several billion dollars). With a proposed budget averaging $2.8 billion annually for the next 5 years, PSD is forecasted to maintain the largest budget of the six divisions within NASA's Science Mission Directorate while supporting a wide range of exploration and research activities recommended by the National Academies of Sciences, Engineering, and Medicine (National Academies) or mandated by Congress. Over the coming decade, NASA is planning to launch missions to return planetary samples from Mars, send spacecraft to Jupiter's moon Europa and Saturn's moon Titan, and work with commercial vendors to send multiple landers to Earth's Moon.

In this audit, we assessed NASA's management of its planetary science portfolio and examined whether PSD is meeting established goals and priorities. Specifically, we evaluated whether the planetary science portfolio is (1) addressing the National Academies' recommendations; (2) maintaining and enhancing its infrastructure, including workforce, support facilities, and technology; (3) achieving technical objectives; and (4) satisfying congressional requirements. To complete this work, we interviewed PSD and other NASA officials, reviewed the status of PSD missions, and reviewed relevant federal and NASA policies and procedures.

WHAT WE FOUND

PSD has taken positive steps in response to recommendations and goals outlined by the National Academies, including actions to (1) implement recommended missions; (2) meet spending goals in the areas of research and analysis, and technology development; (3) address Mars Exploration Program challenges; and (4) further develop radioisotope power. However, as NASA's planetary science missions become more complex, the life-cycle costs within each of PSD's three mission classes are increasing due to project management challenges and mission complexity. For example, Dragonfly, the next New Frontiers mission, has an estimated $2 billion life-cycle cost. Comparatively, prior New Frontiers missions such as Juno and the Origins Spectral Interpretation Resource Identification Security-Regolith Explorer (OSIRIS-REx) had life-cycle costs of roughly $1 billion each. These increasing costs, if not addressed, may result in a reduced cadence of future missions given budget limitations that will mean fewer opportunities to demonstrate new technologies.

While PSD and the Centers are focused on meeting current mission needs, they are at risk of neglecting investments that would help ensure long-term maintenance of NASA's unique planetary science infrastructure. These include (1) sustaining technical capabilities to support future mission needs; (2) a workforce facing increasing risk from an impending wave of retirements that is exacerbated by the lack of sufficient workforce data for management to make informed decisions, challenges associated with transfer of knowledge, and limited awareness of hiring authority best practices; (3) a lack of adequate funding to repair, maintain, and modernize the Deep Space Network, which provides tracking, telemetry, and command services for deep space missions; and (4) funding mid-level technology development. Moreover, the lack of a cohesive "One NASA" approach by stakeholders, including Center management, Mission Directorate management, and NASA's technical workforce, is hindering the Agency's ability to identify, prioritize, and address longer-term risks to planetary science infrastructure.

In examining discrete planetary science missions, the Lunar Discovery and Exploration Program (LDEP) is accepting higher risk than necessary in the Commercial Launch Provider Services (CLPS) project, which provides contracts to U.S. commercial entities to develop landers to deliver NASA science instruments and other payloads to the Moon's surface. Specifically, LDEP has not established a common interface to integrate lunar payloads with the landers from selected CLPS contractors, as advised by the National Academies. Additionally, contracting personnel did not evaluate past performance and financial history risks during their evaluation of prospective CLPS contractors and instead relied on contractors self-certifying future funding availability despite poor business, financial histories, and prior performance. Finally, NASA did not develop safety and mission assurance plans for relevant CLPS task order awards, as required by NASA policy and FAR guidelines. If not adequately addressed, these risks could result in mission failure and the loss of NASA payloads and significant taxpayer investment.

Finally, the Near-Earth Object Observations (NEOO) Program resources remain insufficient to meet the program's congressional mandate of cataloging near-Earth objects (NEO). Scientists classify comets and asteroids that pass within 28 million miles of Earth's orbit as NEOs. In 2005, Congress mandated that NASA detect, track, catalogue, and characterize 90 percent of the NEOs equal to or greater than 140 meters in diameter. However, the Agency has consistently underfunded the NEOO Program. Without substantially increased funding to build a space-based infrared telescope, NASA will likely not meet the mandate until 2040—20 years after the original 2020 goal. Additionally, we identified specific instances of inappropriate use of grants for the construction of telescopes and operation and maintenance of an observatory where a contract would be more appropriate and would provide NASA greater oversight and the ability to minimize risks of improper spending.

WHAT WE RECOMMENDED

To improve NASA's management of its planetary science portfolio, we made 11 recommendations to the Associate Administrator for Science Mission Directorate and Chief Human Capital Officer, including to: (1) communicate to the National Academies realistic costs of planetary science missions and consider resetting the cost caps; (2) identify solutions to adequately fund and sustain critical discipline capabilities; (3) complete an assessment of the Deep Space Network's infrastructure in order to develop and implement a maintenance and upgrade plan to support PSD missions; (4) establish a common interface between instrument and spacecraft for CLPS contractors; (5) evaluate and monitor CLPS contractors' performance and financial capabilities risk; and (6) reassess NEOO Program's priority in meeting the goal of cataloging 90 percent of the NEOs larger than 140 meters.

We provided a draft of this report to NASA management, who concurred with all of our recommendations. We consider management's comments responsive; therefore, the recommendations are resolved and will be closed upon verification and completion of the proposed corrective actions.

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Acronyms

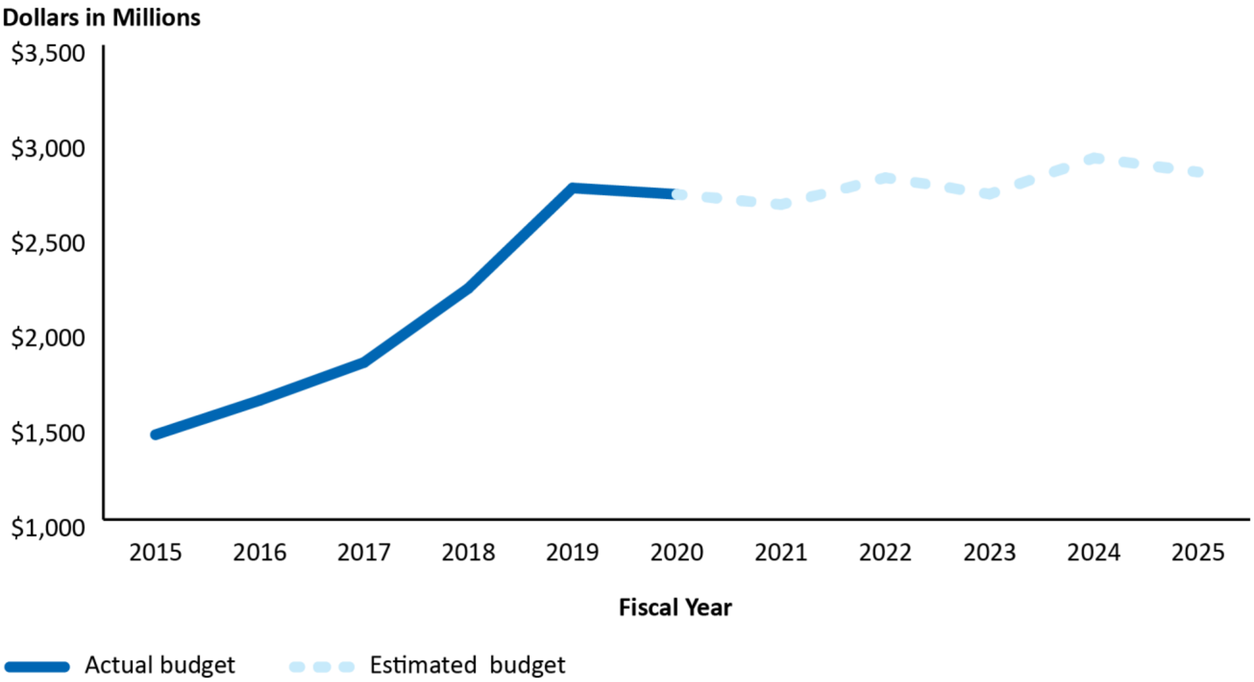
ATLAS	Asteroid Terrestrial-impact Last Alert System
BWG	Beam Waveguide
C.F.R.	Code of Federal Regulations
CLPS	Commercial Lunar Payload Services
CLT	Capability Leadership Team
DART	Double Asteroid Redirection Test
DOE	Department of Energy
DSN	Deep Space Network
FAR	Federal Acquisition Regulation
FY	fiscal year
GAO	Government Accountability Office
HEF	high efficiency
InSight	Interior Exploration using Seismic Investigations, Geodesy and Heat Transport
JPL	Jet Propulsion Laboratory
LDEP	Lunar Discovery and Exploration Program
NEO	near-Earth object
NEOO	Near-Earth Object Observations
NEOSM	Near-Earth Object Surveillance Mission
NEX	NASA Excepted
NPD	NASA Policy Directive
NPR	NASA Procedural Requirements
OCHCO	Office of the Chief Human Capital Officer
OBI	Orbit Beyond Inc.
OIG	Office of Inspector General
OSIRIS-REx	Origins Spectral Interpretation Resource Identification and Security-Regolith Explorer
PDCO	Planetary Defense Coordination Office
PQASP	Project Quality Assurance Surveillance Plan
PSD	Planetary Science Division
RPS	Radioisotope Power Systems
STEM	science, technology, engineering, and mathematics
TRL	Technology Readiness Level
WBS	work breakdown structure

INTRODUCTION

NASA's Planetary Science Division (PSD) is responsible for a portfolio of spacecraft, including orbiters, landers, rovers, and probes, that seek to advance our understanding of the solar system by exploring the Earth's Moon, other planets and their moons, asteroids and comets, and the icy bodies beyond Pluto. Since it was formed in 1958, NASA has sent spacecraft to every planet and many small planetary bodies across the solar system. External stakeholders heavily influence PSD's portfolio, with the Division supporting a wide range of exploration and research activities recommended by the National Academies of Sciences, Engineering, and Medicine (National Academies) or mandated by Congress.

The planetary science portfolio budget has grown from $1.4 billion in fiscal year (FY) 2015 to $2.7 billion in FY 2020 (see Figure 1). With proposed budgets averaging $2.8 billion annually for the next 5 years, PSD is forecasted to maintain the largest budget of the six divisions within NASA's Science Mission Directorate.[1] Over the coming decade, NASA is planning to launch missions to bring home planetary samples from Mars, send spacecraft to Jupiter's moon Europa and Saturn's moon Titan, and send a series of landers to Earth's Moon using commercial vendors, among other endeavors.

Figure 1: PSD Budget, FYs 2015 through 2025



Source: NASA Office of Inspector General (OIG) presentation of PSD budget data extracted from annual budget requests.

[1] The Science Mission Directorate also includes the Astrophysics Division, Biological and Physical Sciences Division, Earth Science Division, Heliophysics Division, and the Joint Agency Satellite Division. In FY 2018, PSD surpassed the Earth Science Division as the division with the largest budget.

In this audit, we assessed NASA's management of its planetary science portfolio and examined whether PSD is meeting established goals and priorities. Specifically, we evaluated whether the planetary science portfolio is (1) addressing the National Academies' recommendations, (2) maintaining and enhancing its infrastructure (i.e., workforce, support facilities, and technology), (3) achieving technical objectives, and (4) satisfying congressional requirements. See Appendix A for details on our scope and methodology.

Background

Since its inception, NASA's planetary science program has sought to understand the solar system while advancing the capabilities of spacecraft and robotic engineering. Planetary scientists are studying the atmospheres and surfaces of planets, determining their origins, and identifying characteristics of asteroids that may present a hazard to Earth. For the first time, NASA plans to conduct missions that will return samples from Mars and an asteroid. Planetary science work will potentially enable future robotic or human exploration throughout the solar system.

Planetary Science Division Strategic Objective and Science Goals

PSD's strategic objective is to understand our solar system's planets and smaller bodies. In support of this objective, PSD aims to achieve five overarching science goals:

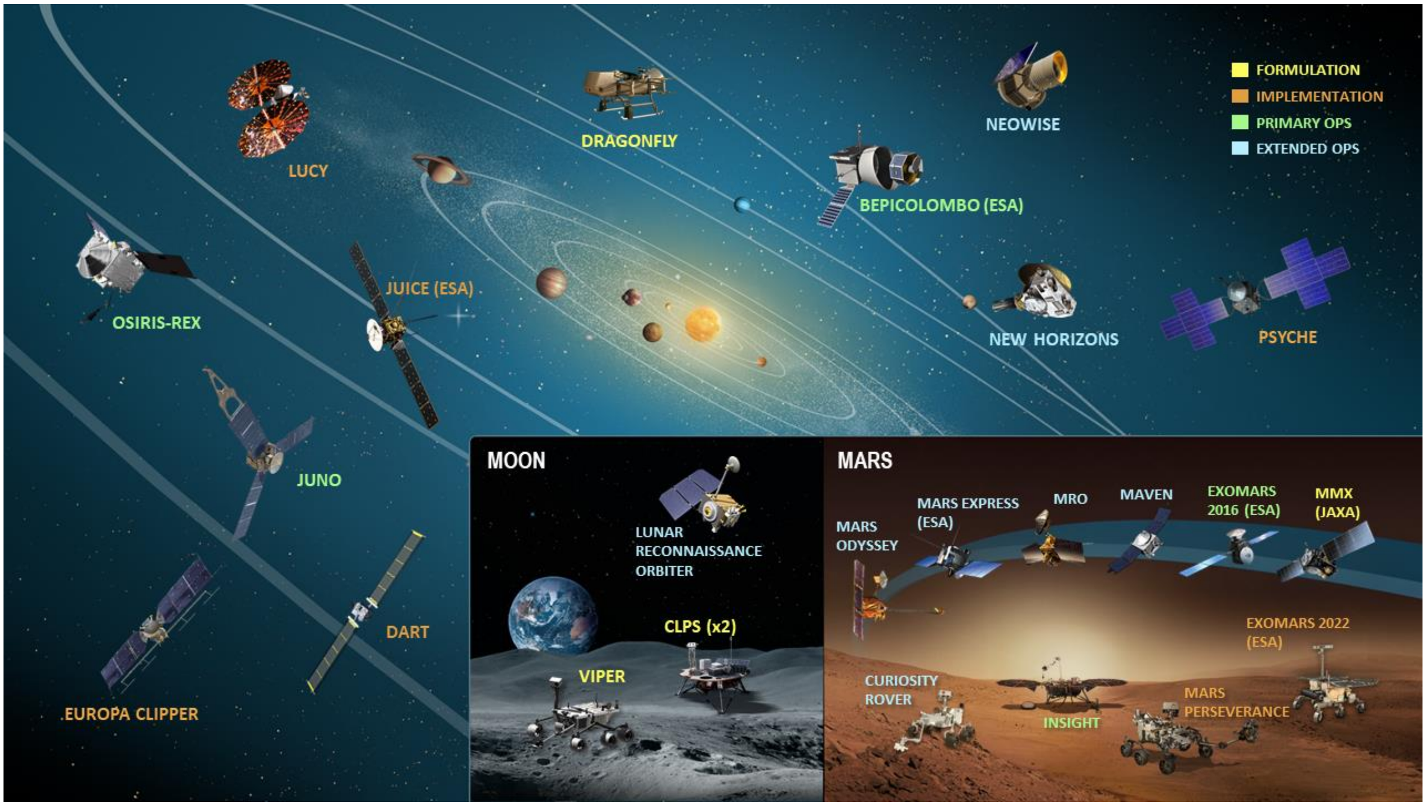
1. Advance the understanding of how the chemical and physical processes in our solar system operate, interact, and evolve.
2. Explore and observe the objects in the solar system to understand how they formed and evolved.
3. Explore and find locations where life could have existed or could exist today.
4. Improve our understanding of the origin and evolution of life on Earth to guide our search for life elsewhere.
5. Identify and characterize objects in the solar system that pose threats to Earth or offer resources for human exploration.

Planetary Science Portfolio Programs and Missions

The planetary science portfolio is composed of eight programs—Discovery, New Frontiers, Mars Exploration, Lunar Discovery and Exploration, Outer Planets and Ocean Worlds, Planetary Science Research, Planetary Defense, and Radioisotope Power Systems—consisting of 30 space flight missions in various stages of operation.[2] Specifically, eight missions are in implementation, five in primary operations, eight in extended operations, and nine are future missions (see Figure 2).

[2] The Lunar Discovery and Exploration Program is not organizationally located under PSD but is instead managed by the Deputy Associate Administrator for Exploration within the Science Mission Directorate. However, the work of this office is part of NASA's planetary science portfolio and its funding is provided within PSD's annual budget allocation. For simplicity, we address Lunar Discovery and Exploration Program projects and tasks as part of the planetary science portfolio throughout this report.

Figure 2: Selected Current and Upcoming Missions within the Planetary Science Portfolio



Source: NASA.

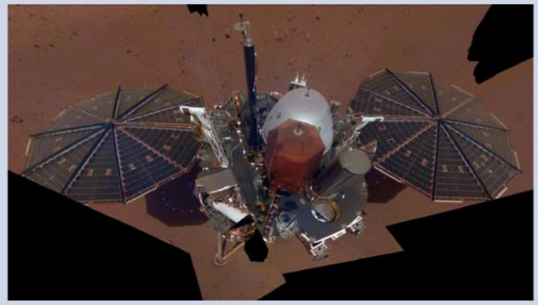
Note: The following four prospective missions are not reflected above: LunaH-Map (Implementation), Europa Lander (Pre-Formulation), Mars Sample Return (Pre-Formulation), Janus (Formulation), Lunar Trailblazer (Formulation), and Near-Earth Object Surveillance Mission (Formulation).

PSD's missions are categorized as small, medium, or large class. Small- and medium-class missions fall under the Discovery or New Frontiers programs, respectively. Large-class missions, also known as Flagship missions, are scattered across several programs based on the mission's objectives and science goals. Flagship missions are directed by NASA or Congress, rather than selected by PSD from proposals submitted by NASA centers or partners and can cost several billion dollars. These missions are strategic in nature and designed to address a wide range of important science objectives at high-priority targets and typically carry a large and sophisticated payload of instruments. Current Flagship missions are being managed under the Mars Exploration Program and the Outer Planets and Ocean Worlds Program.

Discovery Program

The Discovery Program supports small-class missions—those missions that have development costs capped at $500 million—that explore planetary bodies as well as comets and asteroids.[3] These missions are the smallest in scope and have a regular, predictable, and rapid launch cadence (the goal being 24 months or less). Discovery missions are competed, meaning that NASA solicits proposals and selects from concepts developed by principal investigators.[4] The Agency is currently managing three Discovery missions: the Interior Exploration using Seismic Investigations, Geodesy and Heat Transport (InSight) lander is currently in operation on Mars, while the Lucy and Psyche missions are still in development.[5] PSD is also reviewing proposals from its 2019 solicitation for Discovery missions.[6]

Photo of InSight on the Surface of Mars



Source: NASA/Jet Propulsion Laboratory.

New Frontiers Program

The New Frontiers Program is composed of medium-class missions with estimated development costs under $1 billion.[7] New Frontiers missions are expected to follow a regular, predictable launch cadence of one new mission every 5 years. Similar to Discovery missions, New Frontiers missions are competed, and PSD currently has three missions in operation: New Horizons, Juno, and the Origins Spectral Interpretation Resource Identification Security Regolith Explorer (OSIRIS-REx).[8] The New Frontiers Program is also developing the Dragonfly mission, which will explore the surface of Saturn's moon Titan and demonstrate rotorcraft capabilities.[9]

Illustration of Dragonfly on Saturn's moon Titan

Source: NASA/Applied Physics Laboratory.

[3] The Discovery cost cap includes the development costs of the mission but does not include the launch vehicle or operations costs.

[4] A principal investigator is a researcher who has overall responsibility for all aspects of a funded and/or sponsored research project.

[5] For more information on the InSight, Lucy, and Psyche missions, see Appendix B.

[6] PSD is considering four missions—a Venus atmosphere descent sphere and orbiter, an observer to explore Jupiter's moon Io, an observer to explore Neptune's moon Triton, and a Venus surface-mapping orbiter—of which the Division may select one or two as the next Discovery missions.

[7] Similar to Discovery missions, the New Frontiers cost cap does not include the cost of the launch vehicle or operations costs.

[8] See Appendix B for mission descriptions.

[9] For more information on the Dragonfly mission, see Appendix B.

Mars Exploration Program

The Mars Exploration Program oversees three operating orbiters, the Mars Science Laboratory mission's Curiosity rover, and a series of upcoming missions to return Mars samples to Earth.[10] PSD has four overarching goals for Mars exploration: (1) determine if life ever existed on the planet, (2) characterize the climate, (3) characterize the geology, and (4) prepare for human exploration. In July 2020, NASA launched its next Mars Exploration Program Flagship mission, the Mars 2020 Perseverance rover. Perseverance will seek signs of past life, collect and store a set of samples for return to Earth on a future mission, and test new technology to benefit future robotic or human exploration of Mars.

Perseverance at Kennedy Space Center

Source: NASA/Kim Shiflett.

Lunar Discovery and Exploration Program

The Lunar Discovery and Exploration Program (LDEP) is a key component of NASA's lunar exploration strategy, including supporting the Artemis program.[11] LDEP manages a series of contracts with U.S. commercial entities under the Commercial Lunar Payload Services (CLPS) project to deliver science instruments and other payloads to the lunar surface. In addition to CLPS, LDEP is also developing instruments, small spacecraft (SmallSats), and rovers for the continuation of lunar science.[12] Finally, LDEP is managing operations of the Lunar Reconnaissance Orbiter, which is mapping the Moon's surface.

Outer Planets and Ocean Worlds Program

The Outer Planets and Ocean Worlds Program enables science investigations spanning the diversity of worlds suspected of having large liquid bodies underneath thick layers of ice in the outer solar system. The Europa Clipper is the largest Flagship mission within the Program and plans to fly by Jupiter's moon Europa 44 times over a 4-year period to investigate whether conditions on the moon are potentially suitable for life and it may also identify sites for a future lander mission.[13] In addition, the Program is developing technology to explore the icy moons of Jupiter and Saturn; support European Space Agency efforts to explore the Jupiter system, including the moon Ganymede; and conduct outer planets research.

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[10] The Mars Exploration Program operates three orbiters—Mars Odyssey, Mars Reconnaissance Orbiter, and the Mars Atmosphere and Volatile Evolution orbiters—that conduct science and provide communication and data relay services to and from missions operating on the Martian surface. See Appendix B for more information about these orbiters and other Mars surface missions.

[11] The Artemis program is managed by NASA's Human Exploration and Operations Mission Directorate and represents the largest development of space flight capabilities NASA has attempted since the first Space Shuttle was launched more than 38 years ago. Artemis missions to the Moon will expand the Agency's capabilities to transport crew and large amounts of cargo beyond low Earth orbit.

[12] SmallSats are small satellites roughly the size of a large kitchen refrigerator and generally less than 180 kilograms in mass. In addition, PSD's next planned rover mission is the NASA-built Volatiles Investigating Polar Exploration Rover, which is intended to provide key information on the distribution of volatiles (e.g., water, methane, and hydrogen) on the lunar surface in the Moon's South Pole region.

[13] We previously reported on NASA's management of its Europa missions. See NASA OIG, *Management of NASA's Europa Mission* (IG-19-019, May 29, 2019).

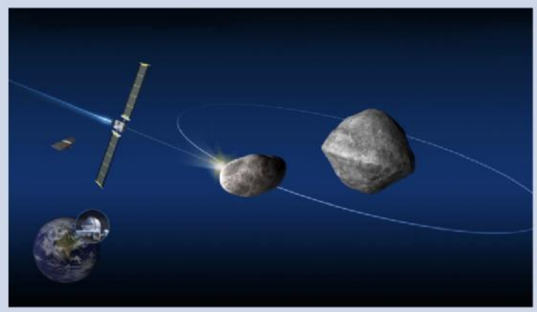
Planetary Science Research Program

The primary purpose of the Planetary Science Research Program is to address the five scientific goals of PSD through analysis of data from NASA missions. The Program also supports PSD activities by collecting, archiving, and making accessible digital data produced by NASA's planetary missions, research programs, and data analysis. Through analysis of this data, the Program develops new theories and instrumentation concepts that enable the next generation of space flight missions. For example, it identified that Jupiter's magnetic field had changed over time after reviewing data from the Juno mission. The Program also funds staff working on emerging flight projects and instruments. The Planetary Science Research Program also (1) develops and assesses multi-mission software tools for spacecraft navigation, command, and control; (2) assists in mission planning; (3) curates astromaterials (e.g., planetary, lunar, and asteroid samples); and (4) conducts informal education outreach by collaborating with university faculty, graduate students, and the science community through research grants.

Planetary Defense Program

The Planetary Defense Program is responsible for managing NASA's efforts to mitigate the effects of a near-Earth object (NEO) event.[14] NEOs are comets and asteroids that pass within 28 million miles of Earth's orbit. The Program's Planetary Defense Coordination Office administers the Near-Earth Object Observations (NEOO) Program, which funds and coordinates efforts to detect, observe, and characterize NEOs that can potentially impact Earth. NEOO's efforts are coordinated with community scientists using ground- and space-based telescopes supported by NASA, the National Science Foundation, and the U.S. Air Force.

Notional Image of DART Impacting Asteroid in Didymos



Source: NASA/Applied Physics Laboratory.

The Planetary Defense Program also manages the Double Asteroid Redirection Test (DART) project, which will demonstrate techniques to change the trajectory of an asteroid in space that could potentially endanger Earth.

Radioisotope Power Systems Program

PSD is supporting efforts to advance radioisotope power technology through investments in new generators and production of plutonium-238 (Pu-238). PSD missions rely on radioisotope power when solar power is not feasible or sufficient to power the spacecraft.[15] The Radioisotope Power Systems Program, managed by Glenn Research Center, is currently developing a next-generation generator as well as expanding capabilities to produce Pu-238 to power those generators. The Department of Energy (DOE) currently maintains about 35 kilograms of Pu-238 isotope designated for NASA missions, about

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[14] NASA is responsible for providing expert input to other federal government agencies such as the Federal Emergency Management Agency in the case of a potential NEO impact.

[15] Solar power is used to generate electricity for most Earth-orbiting spacecraft, as well as for certain missions to the Moon and places beyond that offer sufficient sunlight and natural heat. However, PSD missions that visit some of the harshest, darkest, and coldest locations in the solar system would be impossible or extremely limited without the use of nuclear power.

half of which meets power specifications for space flight. However, in September 2017, the Government Accountability Office (GAO) reported that this supply could be exhausted within the next decade based on NASA's solar system exploration plans.[16] DOE has reestablished the ability to produce Pu-238 for NASA and has plans to increase production to 1.5 kilograms annually by 2026, which NASA forecasts to be sufficient to meet near-term needs.

Planetary Science Division Budget

For FY 2020, PSD's budget was about $2.7 billion, and is anticipated to grow to $2.8 billion over the next 5 fiscal years (see Table 1).

Table 1: Planetary Science Division Budget by Program Area, FYs 2020 through 2025

Program	Fiscal Year (dollars in millions)					
	2020 (actual)	2021 (requested)	2022 (estimated)	2023 (estimated)	2024 (estimated)	2025 (estimated)
Discovery	$506.3	$484.3	$424.4	$434.8	$570.1	$505.8
New Frontiers	142.8	179.0	314.3	332.8	326.9	285.0
Mars Exploration	565.7	528.5	588.4	671.2	798.7	855.3
Lunar Discovery and Exploration	300.0	451.5	517.3	491.3	458.3	458.3
Outer Planets and Ocean Worlds	628.5	414.1	370.7	239.4	192.3	171.7
Planetary Science Research	281.7	305.4	288.6	285.1	295.2	286.7
Planetary Defense	150.0	150.0	147.2	97.6	98.0	98.0
Radioisotope Power Systems	138.5	146.3	150.1	162.8	165.4	169.8
Total	**$2,713.4**	**$2,659.6**	**$2,800.9**	**$2,714.9**	**$2,904.8**	**$2,830.7**

Source: NASA Office of Inspector General (OIG) presentation of PSD budget data.

Note: Numbers may not add up due to rounding.

In May 2019, NASA received an additional $1.6 billion above the President's FY 2020 $21 billion budget request to accelerate the Agency's return to the lunar surface, of which the Science Mission Directorate received an additional $90 million to increase robotic exploration of the Moon's polar regions in advance of a human mission. This resulted in an increase to LDEP's budget from $210 million to $300 million. PSD's mission portfolio and the allocation of its budget are heavily influenced by external stakeholders. Congress at times emphasizes specific goals in the Agency's annual budget authorization through funded or unfunded mandates. For example, in 2013, Congress directed NASA to launch a Europa Orbiter and Lander by 2023 and 2025, respectively. To accomplish this, NASA received approximately $1.26 billion in additional funding for the Outer Planet and Ocean Worlds Program budget between FYs 2013 and 2019 for Europa missions.[17] Congress has also made unfunded mandates to NASA, such as the

[16] GAO, *Space Exploration: DOE Could Improve Planning and Communication Related to Plutonium-238 and Radioisotope Power Systems Production Challenges* (GAO-17-673, September 8, 2017).

[17] Consolidated and Further Continuing Appropriations Act, 2013, Pub. L. No. 113-6 (2013), provided the first direct funding for a mission to Europa. Congress has since changed the planned launch dates to 2025 and 2027, respectively.

enactment of the George E. Brown, Jr. Near-Earth Object Survey Act of 2005.[18] This mandate was intended to further PSD's fifth overarching science goal—identify and characterize objects that pose a threat to Earth—but Congress did not provide additional funding to accomplish the mission.

National Academies Decadal Surveys

The National Aeronautics and Space Administration Authorization Acts of 2005 and 2008 legislatively mandated that NASA conduct decadal surveys and respective midterm reviews in each of the Agency's science divisions.[19] At NASA's request, the National Academies initiated decadal strategy studies based on science community consensus and made recommendations for PSD's overall science goals and objectives.[20] PSD mission priorities and selections are guided by these recommendations as the Division plans out the balance of its missions and direction of its portfolio.

2013 Decadal Survey

The 2013 Planetary Science Decadal Survey (2013 Decadal) identified broad scientific challenges that defined the focus of NASA's planetary sciences research by describing a series of missions, facilities, and programs.[21] The 2013 Decadal also included goals and recommendations as well as suggestions for new missions to help guide the Agency's efforts. Among other things, the National Academies recommended that PSD should do the following:

- Prioritize a (1) Mars sample caching rover, (2) Jupiter Europa orbiter, (3) Uranus Orbiter and Probe, (4) Enceladus Orbiter, and (5) Venus Climate Orbiter, in that order, for Flagship missions over the next decade. The National Academies also prioritized potential missions for the New Frontiers Program.
- Consider de-scoping or delaying Flagship missions in favor of Discovery or New Frontiers missions if there are funding challenges.
- Ensure that high-power uplink and downlink is available to the Deep Space Network, which is the only Earth-based asset available for communication with PSD missions in the outer solar system.[22]
- Restart production of Pu-238 for use in radioisotope power.
- Increase funding for research and analysis programs and establish a significant and steady stream of funding for technology development.

[18] George E. Brown, Jr. Near-Earth Object Survey Act of 2005, Pub. L. No. 109-155, Subtitle C (codified at 42 U.S.C. § 16691) (2005).

[19] National Aeronautics and Space Administration Authorization Act of 2005, Pub. L. No. 109-155 (2005) and National Aeronautics and Space Administration Authorization Act of 2008, Pub. L. No. 110-422 (2008).

[20] Up until July 2015, the research arm of the National Academy of Sciences, Engineering, and Medicine was known as the National Research Council. In 2015, the National Research Council became the National Academies of Sciences, Engineering, and Medicine. For simplicity, we use the term National Academies throughout this report to reference work completed by both the National Research Council and the National Academies of Science, Engineering, and Medicine.

[21] National Academies, *Vision and Voyages for Planetary Science in the Decade 2013-2022* (2011).

[22] Specifically, the National Academies recommended that PSD should maintain high-power uplink capability in the X-band and Ka-band, and downlink capability in the S-, Ka-, and X-bands. Each of these bands is important for communication in certain environments. For example, S-band is the only one that can penetrate the atmosphere of Venus for any potential missions.

2018 Midterm Review

The National Academies published a midterm review in 2018 (2018 Midterm) that assessed the degree to which NASA's current planetary science program was addressing the 2013 Decadal's strategies, goals, and priorities. The 2018 Midterm offered recommendations to NASA for achieving the goals of the 2013 Decadal prior to release of the 2023 decadal survey.[23] For example, the 2018 Midterm recommended that NASA should

- sponsor 8 to 10 concept studies of potential missions for use in prioritizing mission categories in the next decadal survey;
- consider priorities and pathways for advancing CubeSats and SmallSats technology, and how science-driven small mission concepts that leverage emerging capabilities are identified and possibly implemented for flight;[24]
- conduct an assessment of how well the structure and funding of the virtual institutes are aligned with PSD's science goals;[25] and
- as a prospective flagship mission, the results of the NASA Europa lander studies should be evaluated and prioritized within the overall PSD program balance in the next decadal survey.

The 2018 Midterm also assessed the Mars Exploration Program, including the Program's (1) responsiveness to the 2013 Decadal strategies, priorities, and guidelines and relevant National Academies Mars-related reports; (2) long-term goals and ability to optimize science return; (3) relationship to the Mars-related activities of foreign agencies and organizations; and (4) Mars exploration architecture as it relates to representing a reasonably balanced mission portfolio. Additionally, the National Academies commented on other program elements that support the planetary sciences portfolio but are not managed by PSD, including lunar science exploration, space- and Earth-based telescopes, the Deep Space Network, technology research, and education and outreach.

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[23] National Academies, *Visions into Voyages for Planetary Science in the Decade 2013-2022: A Midterm Review* (2018).

[24] NASA's CubeSat Launch Initiative provides opportunities for small satellite payloads built by universities, high schools, and nonprofit organizations to fly on upcoming launches. Through innovative technology partnerships, NASA provides these CubeSat developers a low-cost pathway to conduct scientific investigations and technology demonstrations in space.

[25] NASA's Small Spacecraft Systems Virtual Institute uses web technologies, databases, and virtual collaboration tools to collect, organize, and disseminate small spacecraft knowledge for the benefit of NASA, other government agencies, the public, and the scientific community.

Planetary Science Division Is Generally Meeting Science Goals and Objectives, But Growing Mission Costs May Affect Future Mission Cadence

PSD has taken positive steps in response to recommendations and goals outlined by the National Academies in both its 2013 Decadal and follow-on 2018 Midterm, including actions to (1) implement recommended missions; (2) meet spending goals in the areas of research and analysis, and technology development; (3) address Mars Exploration Program challenges; and (4) further develop radioisotope power. However, the life-cycle costs are growing for each of PSD's mission classes (Discovery, New Frontiers, and Flagship) due to project management challenges and mission complexity. These increasing costs, if not addressed, may result in a reduced cadence of future missions given budget limitations that will result in fewer opportunities to demonstrate new technologies.

Planetary Science Division Is Generally Meeting National Academies Goals

Overall, PSD is meeting the science goals and recommendations outlined by the National Academies in its 2013 Decadal and follow-on 2018 Midterm. In its 2018 Midterm review, the National Academies praised PSD for implementing recommended missions, including the Mars sample return campaign that begins with the Mars 2020 Perseverance rover that launched in July 2020 and future Europa Clipper missions.[26] The 2018 Midterm also noted that PSD had met or exceeded the National Academies' recommended spending for both research and analysis and technology development.[27] PSD has been able to accomplish the National Academies' recommendations, in part, due to increased funding from Congress. For example, since 2013, the annual planetary science portfolio budget generally increased every year from approximately $1.3 billion in FY 2013 to $2.7 billion in FY 2020.

[26] The 2013 Decadal noted that the highest-priority Flagship mission was a three-mission partnership between NASA and the European Space Agency on the Mars Sample Return campaign. Mars 2020 is the first phase of the campaign, with the Perseverance rover tasked with collecting and caching samples for later retrieval. The Europa Orbiter was recommended as the second highest priority mission.

[27] The National Academies recommended that PSD increase spending for research and analysis to develop a wide range of ideas for planetary research. Between FYs 2011 and 2016, PSD increased the Division's spending in this area by 32 percent. The 2013 Decadal also recommended that PSD invest 6 to 8 percent of its budget in technology development to ensure a comprehensive technology portfolio to enable new and more challenging PSD missions. The National Academies determined in its 2018 Midterm that PSD met or exceeded that goal in each year they reviewed.

While the 2018 Midterm review was generally positive about progress PSD has made on recommendations in the 2013 Decadal, it also contained recommendations for additional action. PSD has taken steps to address several of the 2018 Midterm findings and recommendations we considered high risk, including recommendations related to (1) the lack of a Mars exploration strategic plan, (2) the aging Mars communications infrastructure, and (3) a need for enhanced international collaboration. Additionally, PSD continues to address recommendations from the 2013 Decadal relative to Pu-238 and radioisotope power systems (RPS).

Lack of Comprehensive Mars Exploration Strategic Plan

The 2018 Midterm found that the Mars Exploration Program lacked a comprehensive architecture or overarching strategic plan. Specifically, the 2018 Midterm team noted that the Program manages a series of independent, unconnected missions and that there is no overall vision beyond the sample return from Mars. In response, PSD formed the Mars Architecture Strategy Working Group to determine what science could be accomplished after the Mars Sample Return missions and to define the strategic technologies, infrastructure, and partnerships for future missions. The working group plans to report its results in August 2020.

Aging Communication Infrastructure

In the 2018 Midterm, the National Academies identified a risk that ongoing and future missions on the Mars surface would lack the necessary communications and relay support due to a network of aging orbiters circling the planet. PSD needs to have communication and relay capabilities in place to support its various assets on the surface of Mars, including ongoing missions such as the Curiosity rover and the InSight lander and upcoming missions like the Mars 2020 mission's Perseverance rover. Five orbiters are currently in place around the planet that can provide communication and relay capability. However, NASA's three primary orbiters—Mars Odyssey (19 years in operation), Mars Reconnaissance Orbiter (15 years), and the Mars Atmosphere and Volatile Evolution orbiter (7 years)—are all in extended operations far exceeding prior orbiter mission lifespans.[28] PSD officials indicated that both the Mars Reconnaissance Orbiter and Mars Atmosphere and Volatile Evolution have sufficient fuel to maintain their needed positions orbiting Mars until the late 2020s, but the Division may decommission Mars Odyssey as early as 2021. PSD plans to address NASA's aging communication infrastructure risk by supplementing the network with the future Mars Sample Return orbiter—which will provide communications relay support to ground assets while in Mars orbit—as well as planning for a new Mars Ice Mapper orbiter.

[28] In addition to the Agency's three orbiters, the European Space Agency, with contributions from NASA, also operates the Mars Express Orbiter (launched in 2003) and Trace Gas Orbiter (launched in 2016). See Appendix B for descriptions.

International Collaboration

While the 2018 Midterm indicated that international collaboration on Mars assets has been positive despite some challenges on previous missions, it also recommended that NASA work to reinvigorate international coordination to implement Mars exploration more effectively and affordably.[29] In support of this recommendation, PSD has coordinated with several international partners for each of its upcoming missions. For example:

- The Perseverance rover, which launched in July 2020, incorporates instruments from three international partners.[30]
- The Mars Exploration Program is collaborating with the European Space Agency in support of the Mars Sample Return mission. Specifically, the European Space Agency will provide a rover that will retrieve samples cached by NASA's Perseverance rover, as well as a Mars Return Orbiter for returning the samples collected on the planet's surface, both of which are planned to launch in 2026.
- NASA is working with the Canadian Space Agency on development of the Mars Ice Mapper.

Long-Term Development of Plutonium-238 and Radioisotope Power Systems

The 2013 Decadal identified the need for additional Pu-238 for RPS and recommended that NASA work with DOE to maintain steady Pu-238 production and long-term development of advanced energy conversion techniques. For more than 4 decades, NASA missions have relied on RPS to provide power for space flight missions to distant solar system destinations with harsh environments and highly challenging trajectories. For example, the Voyager missions launched in 1977 with an RPS that continues to operate much longer than expected, possibly because of its silicon-germanium technology.[31] That configuration went out of production in the early 2000s and was replaced by the Multi-Mission Radioisotope Thermoelectric Generator (MMRTG), which is currently in use on the Curiosity rover (see Figure 3) and will be used on the Perseverance rover. However, MMRTG is less efficient and will not provide sufficient power over time even compared to the older silicon-germanium RPS technology. Consequently, a more efficient RPS is needed for future large outer world PSD missions.

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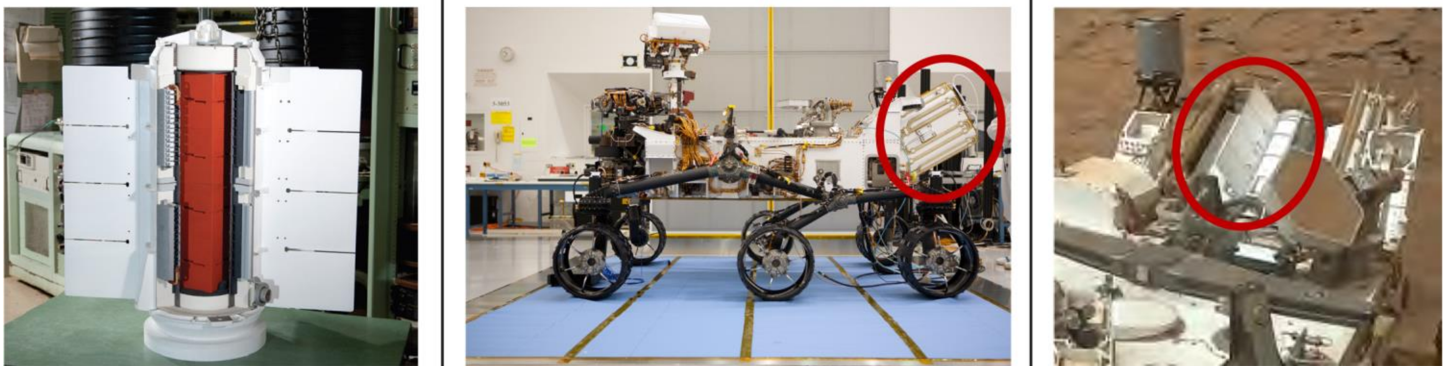
[29] For example, NASA and the European Space Agency were initially joint partners on the development of the ExoMars mission. NASA ended the partnership in 2013 due to funding issues but contributed two radio communications systems to the orbiter. Additionally, the InSight lander experienced a 2-year delay due to the late delivery of a seismometer from the French Space Agency, Centre National d'Etudes Spatiales.

[30] Spain is developing the Mars Environmental Dynamics Analyzer, Norway is developing the Radar Imager for Mars' Subsurface Experiment, and France made significant contributions to the SuperCam at Los Alamos National Laboratory.

[31] NASA launched Voyager 1 and Voyager 2 in 1977 to conduct close-up studies of Jupiter and Saturn, Saturn's rings, and the larger moons of the two planets. With the successful achievement of mission objectives, NASA added flybys of Uranus and Neptune. Each Voyager mission was expected to last 5 years, but instead both have stretched over 40 years. Silicon-germanium technology was first used in the Voyager missions and it was last used with the Cassini (1997) and New Horizons (2005) missions. RPSs made from silicon-germanium-based thermoelectric materials have higher efficiencies than the materials used in the Pioneer and Viking missions in the early to mid-1970s and later in Mars Science Laboratory and Mars 2020 missions. The capability was lost when silicon-germanium went out of production in the early 2000s, with the contractor disbanding the team that created the technology.

Figure 3: Mars Science Laboratory's Use of the Multi-Mission Radioisotope Thermoelectric Generator



Cutaway model of MMRTG. The vertical red blocks in the center are individual heat source modules and the white fins on either side are radiators.

Image of the Mars Science Laboratory mission's Curosity rover with the stucture that will house the MMRTG at the back of the rover (circled in red).

Image of the Mars Science Laboratory on Mars with the MMRTG structure (white object circled in red) visible.

Source: NASA.

In response to the National Academies' recommendation, NASA established three goals for the RPS Program Office:

- *Maturing technology.* NASA has studied and funded the "Next-Generation RTG."
- *Pu-238 production.* About $83 million—half of the RPS Program's annual budget—has been provided to DOE to sustain Pu-238 production.
- *Compliance functions.* The updated Memorandum of Understanding between NASA and DOE, (signed in 2016) increased coordination in restarting Pu-238 production. For NASA this included identifying the RPS Program Office as an ongoing point of contact to coordinate with DOE. The Office also centralized the support needed for flight systems, such as regulatory compliance for ensuring the public safety when launching spacecraft containing nuclear materials.[32]

Despite these steps, PSD faces hurdles to ensure timely advancement in RPS technology. First, mission demand for RPS technology is uncertain and because RPS and Pu-238 production take a significant amount of time to produce, production decisions must be made far in advance of the missions to ensure adequate supply. Second, the RPS Program Office will have to manage communication and oversight capabilities across agencies. Specifically, NASA must ensure that experts located at Glenn Research Center and the Jet Propulsion Laboratory (JPL) can provide timely input to DOE's contractors that prepare the fuel and build the RPS. Finally, PSD is a stakeholder in a nuclear power and propulsion

[32] The National Environmental Policy Act, Pub. L. No. 91-190 (1970), requires all federal agencies to integrate environmental values into their decision-making processes by considering the environmental impacts of their proposed actions and the reasonable alternatives to those actions.

system planning team that is tasked with identifying opportunities to optimize all nuclear investments, including fission power systems, nuclear thermal propulsion for human deep space flight, and other emerging system technology developments.[33]

Notwithstanding these remaining challenges, the actions PSD and the RPS Program Office have taken to date are positive steps in addressing the 2013 Decadal Survey recommendations.

Rising Mission Costs May Affect Future Mission Cadence

As NASA's planetary science missions become more complex, the individual life-cycle costs within each of PSD's three mission classes are increasing.[34] Discovery and New Frontiers missions are competed missions selected under the condition that they do not exceed development cost caps of $500 million and $1 billion, respectively. However, these cost caps do not reflect the total costs of those missions because they do not include launch vehicle and operations costs, which can add hundreds of millions of dollars to each program's overall life-cycle costs. While excluding launch and operation costs may ensure a fairer comparison among competitive missions typically managed by principal investigators since it does not eliminate missions to distant destinations necessitating a longer period of transit, these costs do not change the fact that overall life-cycle costs will be significantly higher than initially projected. For example:

- *Discovery-class missions.* When considering the full life-cycle costs including the launch vehicle and operations, the Lucy and Psyche missions are projected to cost $981 million and $996 million, respectively. This is closer in value to the $1 billion cost of a New Frontiers-class mission. Comparatively, even after experiencing a 2-year delay and a resulting $150 million cost increase, the InSight mission's estimated total life-cycle cost was $829 million. Even when excluding launch vehicle and operations costs, none of the Discovery missions are under the $500 million cost cap.
- *New Frontiers-class missions*. Dragonfly, the next New Frontiers mission, has an estimated $2 billion life-cycle cost, compared to the current Flagship Mars 2020 mission's estimated life-cycle cost of $2.7 billion prior to launch. Comparatively, prior New Frontiers missions such as Juno and OSIRIS-REx had life-cycle costs of roughly $1 billion each.
- *Flagship-class missions*. Current Flagship missions, such as Mars 2020 and Europa Clipper, have life-cycle costs in the multi-billion-dollar range. Specifically, prior to launch, Mars 2020 costs are estimated at $2.7 billion, while Europa costs are estimated at $4.3 billion.

Table 2 reflects the life-cycle costs of recent and current missions within each mission class.

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[33] Fission Power Systems such as the Kilowatt Reactor Using Stirling Technology system first tested in 2017, uses Stirling converters, shielding, sodium heat pipes, neutron reflector, and a uranium core to create a stable self-sustaining power producing reaction. Fission Power Systems are the only power sources currently envisioned to enable sustained human surface operations on the Moon and Mars. These systems also provide a viable option for larger science missions. Where NASA funds plutonium production as a primary user, uranium could be obtained from existing users.

[34] PSD missions follow NASA's project life cycle, which is divided into two primary phases—Formulation and Implementation—that are further divided into additional phases, milestones, and key decision points. In the Formulation phase, mission teams identify how their mission supports NASA's strategic goals and develop project designs. Once in the Implementation Phase, the project conducts (1) final design and fabrication; (2) system assembly, integration, test, launch, and checkout; (3) operations and sustainment; and (4) closeout. Life-cycle costs include all costs associated with each of the project phases.

Table 2: Summary of Mission Costs Considered for the Mission Class Caps and Life-Cycle Costs (Dollars in millions)

Mission	Mission Costs Considered for Mission Cost Cap	Project Life-Cycle Costs
Discovery ($500 million cost cap)		
InSight	$593.9	$828.9
Lucy	505.7	981.1
Psyche	626.3	996.4
New Frontiers ($1 billion cost cap)		
OSIRIS-REx	622.0	1,121.4
Dragonfly	n/a[a]	1,800 - 2,200.0[a]
Flagship (No cost cap)		
Mars Science Laboratory/Curiosity rover	n/a[b]	2,476.3
Mars 2020/Perseverance rover	n/a[b]	2,725.8
Europa Clipper	n/a[b]	4,250.0

Source: NASA OIG presentation of PSD mission information.

[a] As a newly-selected mission, Dragonfly has not yet completed an Agency Baseline Commitment fully establishing proposed costs.

[b] Flagship missions are not held to a cost cap.

In many cases, PSD's mission cost increases have been driven by project management challenges such as technological and parts quality problems. For example, the InSight missions encountered a 2-year delay and $150 million cost increase due to the mission's international partner experiencing technological issues with the lander's vacuum for its seismometer.[35] Additionally, we have found that parts quality and availability of spare parts have increased costs and affected schedule margins for other projects. For example, the Mars Science Laboratory mission experienced a 2-year delay that resulted, in part, from the late delivery of parts. Furthermore, the actuators for the mission's Curiosity rover missed their delivery date by 11 months due to technological problems.[36] As a result of the delay, the life-cycle costs for the Mars Science Laboratory mission grew from $1.6 billion to $2.5 billion. In addition, monthly status reports for DART, Europa Clipper, Lucy, and Psyche show that those missions experienced risks of long-lead times or increased costs for some difficult-to-produce electronic parts.[37]

[35] Specifically, one of InSight's primary instruments, the Seismic Experiment for Interior Structure, provided by the French space agency, Centre National d'Etudes Spatiales, suffered a series of vacuum leaks that NASA concluded could not be fixed in time to permit a launch. JPL took the lead in redesigning the chamber that contained the instrument while the French space agency focused on the instrument's sensors and the final integration of the instrument on the spacecraft.

[36] Actuators are the motors that move the joints in the Curiosity rover's arm, in the sample handling mechanism, and in the wheels.

[37] Specifically, the DART mission has limited spare parts in the event of a hardware failure, which would result in schedule delays to procure those spares. Europa Clipper experienced delays in the acquisition of power and avionics spare parts, as well as electronic parts. Lucy experienced a $450,000 cost growth for electronic parts needed for its Long Range Reconnaissance Imager instrument. Psyche is experiencing longer-than-expected lead times for procuring electronic parts for one of its instruments, the Gamma Ray and Neutron Spectrometer.

PSD's budget has steadily increased over the past 7 years to meet the growing needs of its mission portfolio; however, PSD may have to reduce the cadence of missions as individual missions continue to experience cost growth. Even with the increases in funding, PSD has struggled to meet the National Academies recommended cadence of five Discovery and two New Frontiers announcements every 10 years. Since the 2013 Decadal, PSD has announced solicitations for three Discovery missions—Lucy, Psyche, and a yet to be selected mission—and one New Frontiers mission—Dragonfly.[38] Further, much of PSD's funding is tied to Flagship missions that NASA or Congress has directed, potentially impacting NASA's ability to balance future priorities within the portfolio. For example, NASA directed the Mars sample return campaign and Congress directed, and supported with additional funding, NASA to develop the Europa Clipper mission. As noted earlier, each of these missions is expected to cost multiple billions of dollars and continued congressional support is not guaranteed.

A reduced cadence of PSD missions will result in fewer opportunities for technology demonstration. In order for technologies to mature, they need to demonstrate the capability to work in flight. For example, NASA could benefit from advancing the capability and technology to store and use cryogenic fluids in space for multiple years, which is a key technology for spacecraft propulsion to support longer flight times to distant destinations. However, many such projects have waited years in the technology "valley of death" for a flight demonstration (further discussed in the following section).[39]

[38] NASA officials have told us that they may select two Discovery missions from a 2019 solicitation for Discovery missions, which would bring the current total to four Discovery announcements in this decade.

[39] The valley of death refers to a lack of opportunities to advance technologies that are in the early to middle stages of development. Without a project sponsor or resources, these technologies get stuck in development.

Deteriorating Infrastructure Places Planetary Science Technical Capabilities and Future Missions at Risk

While PSD and the Centers are focused on meeting current mission needs, they are at risk of neglecting investments that would ensure long-term maintenance of NASA's unique planetary science infrastructure. These include understanding the complexities of sustaining technical capabilities and workforce, maintaining the Deep Space Network, and funding technology development. The lack of a cohesive "One NASA" approach by stakeholders, including Center management, Mission Directorate management, and NASA's technical workforce, is hindering the Agency's ability to identify, prioritize, and address longer term risks to planetary science infrastructure.

Planetary Science Division Needs More Focused Efforts to Sustain Technical Capabilities and Support Future Missions

NASA relies on numerous technical capabilities to achieve its diverse and challenging goals. These technical capabilities include NASA and contractor workforces, specialized facilities, and unique tools and production techniques. Centers are managing these technical capabilities in support of specific missions, programs, projects, and research activities. While mission managers, such as those in PSD, have a vested interest in the broader NASA infrastructure, they are especially interested in ensuring adequate availability of those technical capabilities that support the Division's missions.

Since 2012, the Office of the Chief Engineer has formed various teams to assess NASA's technical capabilities.[40] For the purpose of this audit, we focused on the discipline Capability Leadership Teams (CLT) assessment results and how they relate to the work of PSD. The discipline CLTs were composed of the Agency's 19 technical discipline teams.[41] The status of these capabilities directly impact PSD's ability

[40] In June 2012, NASA established the Technical Capabilities Assessment Team to identify and assess Agency technical capabilities and make recommendations for investing in, consolidating, or eliminating capabilities based on mission requirements. Between 2014 and 2015, this work was handed over to the Capability Leadership Teams within their Capability Leadership Model. The discipline Capability Leadership Teams were disbanded in 2018, but some members of the Capability Leadership Teams joined their corresponding long-standing Technical Discipline Teams to continue a less intensive version of the work. Technical Discipline Teams are composed of independent technical specialists from the 19 technical engineering disciplines under the NASA Engineering and Safety Center and function as engineering problem solvers and thinkers for their disciplines.

[41] The 19 technical discipline teams are Aerosciences; Avionics; Cryogenics; Electrical Power; Flight Mechanics; Guidance, Navigation, and Control; Human Factors; Life Support/Active Thermal; Loads and Dynamics; Materials; Mechanical Systems; Non-Destructive Evaluation; Passive Thermal; Propulsion; Sensors and Instruments; Software; Space Environments; Structures; and Systems Engineering.

to effectively and efficiently accomplish mission goals. For example, the Avionics, Guidance Navigation Control, Materials, and Propulsion discipline capabilities are critical to PSD missions such as DART, Europa Clipper, Lucy, Mars 2020, and Psyche.

During a series of annual reviews between 2014 and 2018, the discipline CLTs gathered technical capability data, including those specific to PSD missions. Between 2017 and 2018, the discipline CLTs reported moderate to high levels of risk associated with various NASA capabilities. Of the 19 discipline CLTs, 16 reported medium- to high-risk in workforce, 12 in technology development, 9 in tools, and 3 in facilities. Additionally, the CLTs identified management funding decisions incorporated in the current full cost accounting framework as one of the underlying causes for the increased risks to capabilities. Specifically, management may have inadvertently neglected future mission needs when allocating certain costs.[42] As the principle is currently applied to the disciplines, full cost accounting consumes current assets but does not provide a means to replenish them for future missions. According to several management officials, the CLTs were disbanded in 2018 because the majority of the work was completed, and the remaining items were passed to other teams. At the same time, the Centers are responsible for aligning their internal investments to sustain and develop these technical capabilities.

In its simplest terms, the full cost accounting method assigns Centers' direct and indirect costs to individual projects and flight missions. While project managers try to minimize cost charges to their projects, Centers would like to maximize usage of their capabilities to support flight missions, projects, or research. Specifically, technical resources are developed, managed, and provided by the Centers, while the Mission Directorates, which manage the projects and flight missions, pay the Centers for the resources they require. For example, to test and assess radiation risk and develop radiation risk mitigation activities, the Europa Lander mission paid for the space environment technical capabilities of test chambers at Goddard Space Flight Center, JPL, and Marshall Space Flight Center.

Mission owners like PSD are focused on minimizing the costs of individual projects and missions, and inherently are disincentivized to share in the additional costs to fund Center technical capabilities beyond what they need for their projects, such as supporting development for future missions. Likewise, Centers have limited discretionary funding available to sustain capabilities not in use by current projects and missions or to invest in new capabilities or expand capabilities for prospective missions. For example, the space environments capability is maintaining approximately 300 personnel who are currently fully engaged in multiple programs. The Centers do not have the resources to hire additional personnel before expertise leaves (e.g., retirement or another job), provide other than on-the-job training, and are hesitant to hire additional personnel because of the uncertainty of future projects requiring these resources. While addressing these issues may be critical to future missions, in our opinion current cost accounting practices are not leveraged to support such investments.

In our judgement, it is the responsibility of NASA senior management to establish an organizational structure that enables planning, executing, controlling, and assessing the Agency-wide organizational needs to achieve long-term objectives. NASA risks the efficiency and efficacy of future missions by failing to ensure adequate investment in mission critical capabilities.

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[42] NASA Procedural Requirements (NPR) 9060.1A, *Accrual Accounting - Revenues, Expenses, and Program Costs* (May 2, 2016); and Statement of Federal Financial Accounting Standards (SFFAS) No. 4, *Managerial Cost Accounting Standards and Concepts* (June 30, 2019).

Planetary Science Division Not Adequately Assessing and Mitigating Workforce Risks

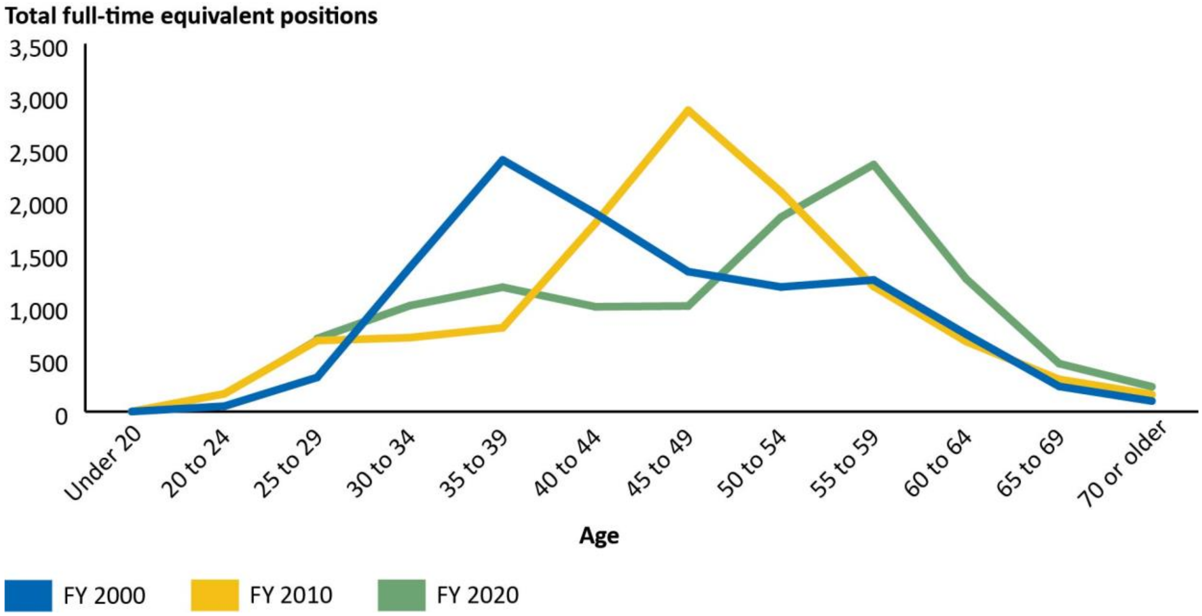
In recent years, the NASA OIG and GAO have reported on multiple NASA projects—including the Europa Clipper, Mars 2020, and Surface Water and Ocean Topography missions—that have experienced varied workforce challenges such as not having enough staff or staff with the right skills.[43] For example, in our May 2019 report on the Europa mission, we found that the JPL workforce assigned to the Clipper was persistently understaffed, particularly in critical areas such as the mechanical and electrical cable harness subsystem, science instruments, and avionics. There are several factors contributing to these workforce challenges with the first and foremost being the growing risk from an impending wave of retirement. Furthermore, the ability to mitigate the risk posed by future retirements is hampered by a lack of retirement and staffing data applicable to the key technical disciplines, challenges in ensuring a robust workforce pipeline, and execution of available hiring flexibilities.

NASA Faces a Growing Wave of Retirements

Exacerbating NASA's workforce challenges is a potential retirement wave that could result in a significant loss of institutional knowledge and skills. Over the past 4 years, NASA's civil servant headcount has remained constant at around 17,000 employees, with about 11,000 (65 percent) of these employees falling under the occupation category "science and engineering"—the part of the workforce that provides technical capabilities to enable space flight missions. Within the science and engineering category, 6,000 of those 11,000 employees are more than 50 years old. Additionally, approximately 3,200 employees are currently eligible to retire in 2020, with an additional 2,000 employees becoming eligible within the next 5 years. (See Figure 4 for a breakdown of the science and engineering workforce by age.)

[43] GAO, *NASA: Assessments of Major Projects* (GAO-18-280SP, May 1, 2018); and NASA OIG, *2019 Report on NASA's Top Management and Performance Challenges* (November 13, 2019), *Management of NASA's Europa Mission* (IG-19-019, May 29, 2019), *NASA's Surface Water and Ocean Topography Mission* (IG-18-011, January 17, 2018), and *NASA's Mars 2020 Project* (IG-17-009, January 30, 2017). Scheduled to launch in April 2021, the Surface Water and Ocean Topography mission is a satellite mission that will produce the first global survey of Earth's surface water, observe details of the ocean's surface topography, and measure how water bodies change over time.

Figure 4: Science and Engineering Workforce Trend, as of March 2020



Source: NASA OIG presentation of Agency workforce data.

Note: Agency data does not include JPL, a contractor-owned facility, workforce data.

Although NASA's current human resources modeling predicts only a small overall reduction in the Agency's science and engineering workforce over the next 5 years, we found this modeling lacks the granularity to predict and assess the effect of losses on specific technical disciplines. In some instances, the loss of a sole expert could be detrimental to a project because certain science and engineering skills are unique to NASA, as was the case, for example, with the loss of silicon-germanium RPS technology. Overwhelmingly, 15 of the 19 discipline CLTs rated their workforce challenges at medium risk with a 16th team rating their workforce as high risk, and nearly half indicated the status was worsening. In 2019, the Active Thermal CLT raised their workforce risk from medium to high as five senior thermal engineers put in their retirement notices and Center management had no succession plans in place. As of May 2020, four of the five engineers have retired with the fifth engineer expected to retire later in the year. Additionally, the Active Thermal discipline expects two to three more retirements over the next couple of years. These engineers were unique technical specialists in the Active Thermal's subdisciplines areas of loop heat pipes, thermal control, cooling fluids, and fluid dynamics, all of which are critical for PSD missions. Likewise, the Materials CLT's assessment found some of the technical discipline specialties were staffed by only one or two people, all of which were eligible to retire.

Current Workforce Data Is Insufficient for Management to Make Informed Decisions

Detailed engineering subdiscipline workforce data is not readily available for NASA management to make informed decisions. Our review found that the workforce data gathered from NASA's payroll system and used in the Agency human resources modeling of the science and engineering workforce uses job codes that do not align with the Agency's engineering technical subdisciplines as defined during the discipline CLT reviews. The data gathered during the CLT reviews presented a more granular picture of the skillsets within NASA's science and engineering workforce. However, this data was collected manually by the technical disciplines and kept by the discipline CLTs in spreadsheets that were never aggregated or reconciled to the Agency's payroll system data.

The workforce data points provided by the discipline CLTs were a one-time effort to obtain a snapshot on the state of NASA's 19 technical disciplines. In general, the teams found the data collection process an instructive investment to redefine their disciplines' underlying subdiscipline and specialized skillsets. However, we believe the process could have been improved as participation was mixed, skillset definitions were still being refined, and there was a potential for double counting because of staffing overlap between disciplines. The responsibility for maintaining the capabilities has shifted solely to the Centers, and as of May 2020, it was unclear as to the type of capability data that will be collected and shared. Prospectively, the presentation of the Center based data collection will be through the Office of the Chief Human Capital Officer (OCHCO), as they were expected to issue the first annual human capital master plan in May 2020. Although the Centers are responsible for collecting data and communicating information to support this and future workforce plans, it is not clear whether Centers will collect subdiscipline-level data and reconcile the information with existing Agency workforce data systems (e.g., the payroll system).

Consistent with Office of Management and Budget's Circular No. A-123, and Standards for Internal Control in the Federal Government, NASA management should define and identify the information requirements at the relevant level needed to address risks.[44] For NASA, knowing whether engineers with the right skillsets will be available for future projects is fundamental to human capital strategic planning. Without this information, it is unclear how NASA management and Centers can accurately develop human capital master plans or determine the available skillsets for future PSD missions.

Transfer of Knowledge Has Proved Challenging

Mentoring

In recent years, NASA has attempted to address its impending retirement wave by hiring recent college graduates into entry-level career engineer's positions and has long acknowledged the importance of mentoring these new hires.[45] Furthermore, the National Academies recently recommended shifting away from a culture of ad hoc mentorship and toward one of intentional, inclusive, and effective mentorship in all institutional contexts.[46] Several discipline CLTs noted that many of the unique skills required for NASA are not taught in school but rather are "homegrown" while working on Agency projects. The knowledge transfer process makes filling these skills gaps more challenging as it generally takes new hires several years of job experience to progress to the point where they can contribute more fully. In order to be successful, mentorship requires intentional effort to enable advance hiring, make resources available, and provide development opportunities.

- *Advance hiring.* Advance hiring ensures an overlap between experienced and less experienced staff, but NASA generally lacks the funding to support such hiring. Mentoring requires

[44] GAO*, Standards for Internal Control in the Federal Government* (GAO-14-704G, September 10, 2014). The Green Book provides the overall framework for establishing and maintaining an effective internal control system. Office of Management and Budget Circular No. A-123 provides specific requirements for assessing and reporting on controls in the federal government. The term internal control covers all aspects of an entity's objectives (operations, reporting, and compliance).

[45] Marshall Space Flight Center, *Transmittal of Culture Transfer/Growing Young People Document* (June 8, 1989).

[46] National Academies, *The Science of Effective Mentorship in STEMM* (2019).

intentional effort from both for job shadowing, instruction, and on-the-job-training. According to NASA officials, Centers and technical disciplines have lost and will continue to risk losing unique skills and knowledge because resources are not sufficient to support advance hiring to accommodate overlap. For example, a materials technical expert at Goddard Space Flight Center gave a 2-year notice before retirement; however, the Center's budget did not allow for advance hiring to enable the transfer of that specialist's knowledge and skills to a new hire before his departure. Losing these unique skills and knowledge will likely affect future capabilities to support PSD missions in the next decade and could impact their cost and schedule.

- *Resource availability.* Proper mentoring has been challenging because mentors are not always readily available, and NASA's system for tracking and accounting for project costs may be a disincentive to mentoring. Mentoring a new employee requires dedicating time and effort for senior staff to be available for job shadowing, instruction, and on-the-job-training. Missions and projects are focused on making the most use of the capable senior specialists and little time is allocated for mentorship. Unsurprisingly, these senior staff members are often also retirement eligible, which increases the time pressure to transfer their knowledge before they leave. In addition, the discipline CLTs expressed their opinion that the project work breakdown structure (WBS) is inflexible for rotating both specialists and less experienced engineers across Centers and projects as needed, and Centers and missions do not have charge codes to account for and track mentorship activities.[47] Unplanned inter-Center research and project collaboration work can create opportunities to increase learning experiences and exposure to different parts of the Agency.
- *Development opportunities*. According to the discipline CLTs, leading smaller scope projects also allows engineers to gain experience while they receive guidance from experienced engineer specialists. However, these smaller projects are harder to come by because such funding opportunities are limited from either the Centers or Mission Directorates, especially for the discipline fundamental research that aligns well with recent graduates.

Workforce Pipeline

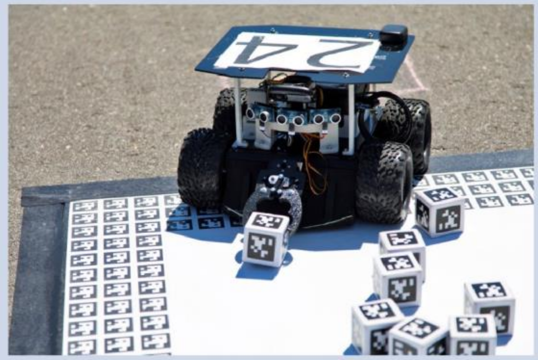
In June 2018, the Executive Director of the American Institute of Aeronautics and Astronautics testified to Congress about a nationwide shortage of workers for jobs requiring science, technology, engineering, arts, and mathematics and suggested that significant investments must be made to address workforce development challenges impacting the entire aerospace community.[48] We found PSD has made continuous as well as contemporaneous efforts in stimulating science, technology, engineering, and mathematics (STEM) interests in high school and college students and attracting potential talent. NASA can build on those efforts to supplement its workforce pipelines.

[47] According to the *NASA Work Breakdown Structure (WBS) Handbook* (NASA/SP-2016-3404, January 2018), WBS is a product-oriented family tree that identifies the hardware, software, services, and all other deliverables required to achieve an end project objective. The purpose of a WBS is to subdivide the project's work content into manageable segments to facilitate planning and control of cost, schedule, and technical content.

[48] Mr. Daniel L. Dumbacher Executive Director American Institute of Aeronautics and Astronautics Subcommittee on Space Committee on Science, Space, and Technology, United States House of Representatives; *NASA's Cost and Schedule Overruns: Acquisitions and Program Management Challenges* (June 14, 2018). The American Institute of Aeronautics and Astronautics' membership includes nearly 30,000 engineers and scientists from 88 countries dedicated to the global aerospace profession. The Institute convenes yearly forums; publishes books, technical journals, and Aerospace America; hosts a collection of 160,000 technical papers; develops and maintains standards; honors and celebrates achievement; and advocates on policy issues.

For more than 25 years, PSD's Robotics Alliance has engaged both high school students and NASA system engineers. Specifically, in addition to serving as an outreach program, the Robotics Alliance is a pipeline for future recruitment and inspiration for NASA technology development as well as an opportunity to develop project leadership skills. Additionally, the Lucy Student Pipeline Accelerator and Competency Enabler provides college undergraduates the opportunity to support NASA's Lucy mission. The student collaboration includes 40 STEM majors at Arizona State University (about 60 percent engineering) and virtual engagement that includes 385 STEM majors (about 66 percent engineering) at another 102 colleges and universities. Moreover, NASA's Office of STEM Engagement—targeted for defunding in the Agency's last four budget requests—spearheads higher education outreach projects and the NASA Engineering and Safety Center's supports post-doc graduate projects that also benefit NASA by increasing the pipeline of students with the skills needed for future PSD missions.

STEM Activities with Robotics



Students from universities and community colleges across the nation recently participated in Swarmathon, pictured here in April 2018 at NASA Kennedy Space Center. Their developments may lead to technology that could help astronauts find needed resources while exploring the Moon or Mars.

Source: NASA.

While the Robotics Alliance and others have been successful in engaging high school and college students, there may be opportunities for PSD and the Centers to leverage these successes to more directly engage in outreach activities in support of at-risk technical disciplines. First, we found that 11 of the 14 technical leaders we surveyed across all Centers had limited or no knowledge of the Office of STEM Engagement.[49] In addition, there is insufficient funding and support from Mission Directorates and Centers for outreach efforts and basic research funding—research which creates a plausible connection to university laboratories. When supported, these activities also serve as way to cultivate technical experience and expertise. For example, the Europa Clipper mission's Instrument Concepts for Europa Exploration 2013 awardees included the California Institute of Technology; University of California, Los Angeles; and JPL working together to advance the state of magnetic field sensors and instruments. Resolving gaps in the engineering capabilities pipeline will require NASA to invest its limited resources more efficiently on proven methods and best practices. Building on current outreach initiatives could help NASA hire and develop the next generation of employees.

[49] We did not survey 5 of the 19 CLTs on this subject.

Hiring Authority Best Practices Are Not Always Communicated to Stakeholders

PSD can employ a variety of Agency special hiring authorities, such as NASA Excepted (NEX) and the Pathways Program, to fill and maintain critical positions.[50] These authorities can further the Centers' abilities to bring in needed workforce to sustain future missions and related technical capabilities. However, NASA is not always clearly communicating with "line management" at the Centers opportunities for utilizing these authorities. Additionally, the discipline CLTs noted a lack of best practices for utilizing temporary hiring authorities.

The NEX employment authority, which has been available since the Agency was created in 1958, provides NASA management officials the flexibility to hire any individual to fill a non-clerical position, on a time-limited appointment, to meet the needs of the Agency. In recent history this special hiring authority had been rarely used, but in April 2019, the NASA Administrator delegated the NEX authority to the OCHCO with instructions to allocate a portion of the 425-total allowed NEX hires to each of the NASA Centers.[51] Since then, the OCHCO has visited all the Centers and met with senior leaders to educate them on how to use the NEX authority. During our audit, total NASA usage of this hiring authority increased from 16 hires in late August 2019 to about 30 as of March 2020, of which 17 are science and engineering positions. However, we found a general lack of awareness of this hiring authority among the project managers we interviewed and at least 12 of the 19 engineering technical disciplines who could likely benefit from its use. In addition, without comprehensive data on critical technical skill needs, PSD lacks the information necessary to effectively and efficiently use this authority.

The Pathways Programs is designed to provide high school and college students with opportunities to work at NASA and explore federal careers while still in school.[52] Unlike the NEX hiring authority, the Pathways Program is commonly used, with nearly every engineering discipline CLT and project noting that the Program has been beneficial. NASA's Pathways Program brings in about 650 interns per year. In 2019, about 330 students were selected for permanent positions through the Pathways Program, of which about 78 percent were science and engineering. However, they also noted shortcomings in the hiring process. For example, USAJOBS.gov, the main portal for federal government job postings, has filters that if not properly applied will remove highly qualified individuals for unintended reasons. Discipline CLTs like Cryogenics, Loads and Dynamics, Mechanical Systems, and Passive Thermal all reported instances of qualified candidates not making the selection list. Additionally, Pathways Program hiring opportunities may not always align with school graduations. For instance, another CLT indicated that in many cases while graduations occur in the spring, NASA did not post hiring opportunities in the previous fall or winter so that students could join the Agency shortly after graduation, increasing the possibility that they would accept a job elsewhere.

With proper guidance, communications, and management controls, the authorities discussed can help fill or retain critical knowledge and disciplines.

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[50] NASA, *NASA Desk Guide on NASA Excepted (NEX) Employment Version 2* (NSREF-3000-0777, August 7, 2019); NPR 3300.1C, *Employment, Appointment Authorities, and Details* (November 1, 2015); and NASA Policy Directive (NPD) 3212.1, *Excepted Service Appointments* (June 1, 2016).

[51] When NASA was created by the National Aeronautics and Space Act of 1958, the Act included the NEX position allowances. National Aeronautics and Space Act of 1958, 51 U.S.C. § 20113(b) (2010).

[52] Intern Employment Program 5 Code of Federal Regulations (C.F.R.) 213.3402 and 5 C.F.R. 362 Excepted Service—Schedule D Excepted Appointment.

NASA Risks Future Planetary Science Division Missions by Not Adequately Funding Deep Space Network Repair and Maintenance

NASA has not adequately funded Deep Space Network (DSN) repair, maintenance, and modernization efforts. NASA's Human Exploration and Operation Mission Directorate manages DSN under the Space Communications and Navigation program. Established in December 1963, DSN provides deep space missions with the tracking, telemetry, and command services needed to control spacecraft and transmit data back to Earth. In FY 2019, DSN supported about 35 NASA and non-NASA missions, of which PSD and its partners managed 12 (see Appendix B for project descriptions). Although DSN is meeting its current operational commitments, in our opinion, budget reductions have impacted the Network's performance and threaten its future reliability.

DSN operates antennas and transmitters at communications complexes in three locations: Goldstone, California; Canberra, Australia; and Madrid, Spain.[53] Most of DSN's facilities and hardware are more than 20 years old and require modernization and expansion to ensure continued service for existing and future missions:

- *70-meter antennas.* Constructed in the mid-1960s and early 1970s, DSN's 70-meter antennas are the largest and oldest facilities in the Network (see Figure 5).[54] All three 70-meter antennas in Goldstone, Canberra, and Madrid experience common problems with transmitters, aging radial-bearing, and gear boxes. Additionally, the 70-meter antenna at Canberra requires extensive maintenance and enhancements to replace its obsolete hardware, which will affect Voyager 2 transmissions between February and December 2020 and prevent the mission from resolving critical spacecraft anomalies. This antenna is the only one on Earth that is oriented appropriately and capable of sending commands to the Voyager 2 spacecraft. Though the antenna enhancements will improve future spacecraft communications and the antenna is able to receive data during the upgrade, it is not able to transmit, and Voyager 2 will not be able to receive new commands from Earth until the upgrade is complete.
- *High Efficiency (HEF) antennas*. Built in the mid-1980s, the 34-meter HEF antennas were the first to support higher-frequency transmissions known as X-band uplinks (see Figure 5).[55] Although each DSN complex contained an HEF antenna, both the Goldstone and Canberra antennas have since been decommissioned. Decommissioning of the Madrid HEF antenna has been delayed as a result of construction delays for a new Beam Waveguide (BWG) antenna (see

[53] The Space Communications and Navigation's three communications networks—the Space Network, the Near Earth Network, and DSN—provide secure and adaptable communication services to NASA missions, as well as external customers. External customers include foreign governments, international partners, commercial entities such as launch service providers, and non-NASA U.S. missions.

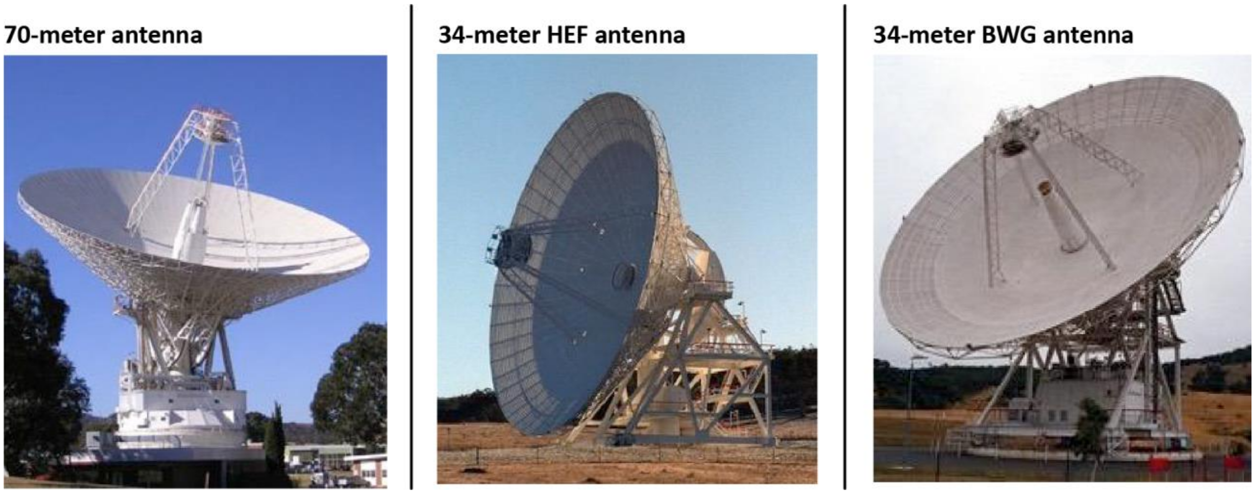
[54] Originally constructed as 64-meter antennas, they were later expanded to 70 meters to increase their ability in gathering weak microwave signals, particularly from the Voyager 1 and 2 spacecraft launched in 1977.

[55] The microwave spectrum is usually defined as a range of frequencies ranging from 1 GHz to over 100 GHz. This range has been divided into a number of frequency bands, each represented by a letter. Ka-band as defined by the Institute of Electrical and Electronics Engineers is a frequency range from 27 to 40 GHz. Ka-band is mainly used for communications with satellites, and provides significantly greater downlink capability; S-band is specifically needed for communications through the Venus atmosphere to the surface; while X-band is needed to communicate through Titan's atmosphere and for spacecraft emergencies.

below). More than 30 years old, the Madrid HEF antenna requires hardware repair and information technology security upgrades to continue operating.

- *34-meter BWG antennas*. Built between the mid-1990s and early 2000s to augment the 70-meter antennas, DSN's eight BWG antennas handle communications in S-, X-, and Ka-band frequencies to support a greater variety of deep space missions (see Figure 5). DSN is currently constructing four additional 34-meter BWG antennas to be completed by 2025; however, construction and subcontractor issues have delayed three of these antennas. To compensate for the delays, DSN deferred decommissioning the Madrid HEF antenna at a cost of about $1 million a year until the new BWG antennas are operational. Of the BWG antennas currently in operation, only two are operating at full capability, while the others have a variety of problems with transmitter, antenna, bearings, pedestal, and Ka-band functionality.

Figure 5: Deep Space Network Antennas



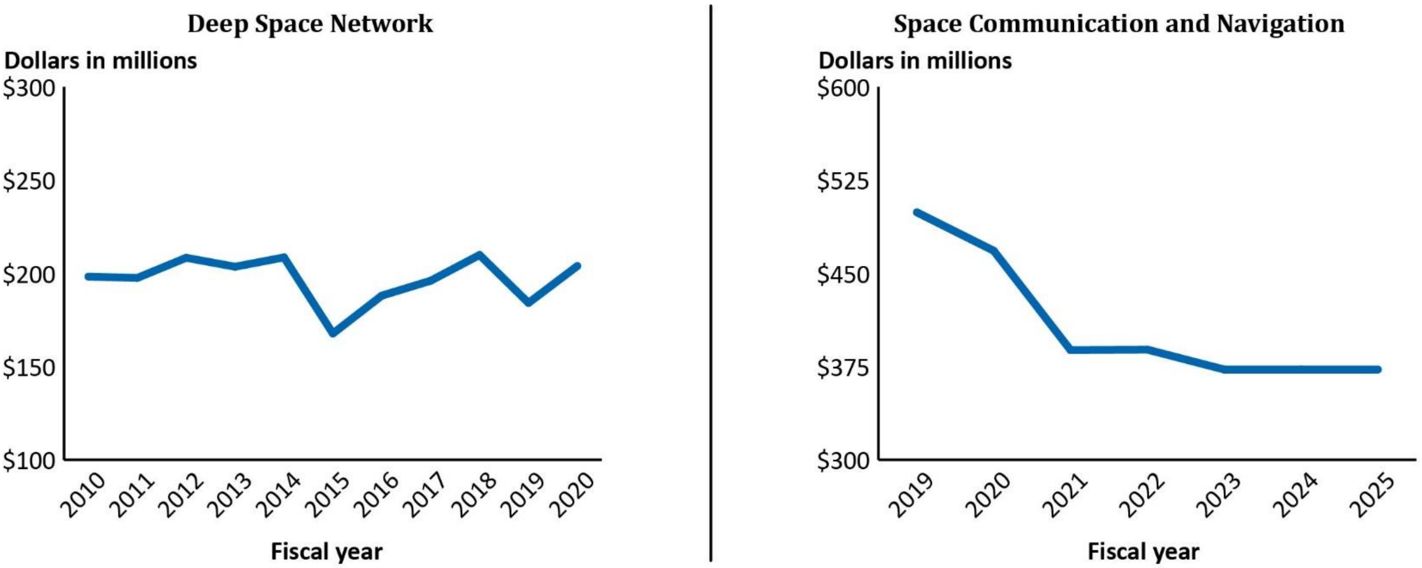
Source: NASA/JPL.

Additionally, two Goldstone facilities are experiencing problems. Specifically, the Goldstone BWG Test Facility is aging and currently has only marginal heating and cooling capability. The Goldstone Solar System Radar, used by PSD to track NEOs, is also currently not operational due to failures of the high-power amplifier and the temporary replacement amplifier, which were used for radio frequency telecommunications and radar transmissions.

The 2013 Decadal recommended that all three DSN complexes should maintain high-power uplink capabilities in the X- and Ka-bands, and downlink capabilities in the S-, X-, and Ka-bands. In addition, the 2013 Decadal recommended that NASA expand DSN capabilities to meet the navigation and communication requirements of upcoming recommended missions. The National Academies found during the 2018 Midterm that the Agency has made progress toward the 2013 Decadal recommendations with its commitment to constructing four new 34-meter BWG antennas with X- and Ka-band capability. However, the recommendation for Ka-band uplink and downlink at all stations has not yet been implemented and uplink capability is only available at Goldstone.

Despite this progress, budget constraints will make it difficult for DSN to maintain its current performance levels while also completing the necessary upgrades to support future PSD missions. Specifically, DSN's annual budget has been cut several times in the past decade and has not improved significantly above its 2012 appropriation of $208 million.[56] Moreover, the DSN budget could be further impacted by the Space Communications and Navigation reduced budget request of $126 million (27 percent) anticipated between FYs 2020 through 2023 (see Figure 6).

Figure 6: Deep Space Network and Space Communications and Navigation Funding



Source: NASA OIG presentation of Agency data.

A Space Communications and Navigation official said that by implementing alternative operational measures to help control costs, DSN has the ability and resources to support the missions planned as well as complete the necessary repairs with the current planned budgets. Despite this claim, we found DSN is delaying maintenance and upgrades to its antennas, including the 70-meter antennas and the Madrid HEF antenna, which could potentially impact future missions. Of the 19 DSN antennas and radar, only 2 are fully functional, 8 need various levels of mechanical and electrical repair, 2 are restricted to limited operations, 4 are not yet built, 2 are decommissioned, and 1 is nonoperational. Sustaining adequate resources for maintenance and expansion of DSN is necessary to fully implement 2013 Decadal recommendations and keep pace with new and evolving mission demands. Consequently, if its budget continues to trend downward, DSN could face an increased risk that it will be unable to meet future operation commitments and support planetary mission data transmissions. Without DSN services, space hardware worth tens of billions of dollars will be little more than interplanetary debris unable to communicate with Earth.

[56] Budget cuts were due to appropriation reductions in the Human Exploration and Operation Mission Directorate.

Mid-Level Technology Development Could Be Better Supported for Future Missions

PSD and the Space Technology Mission Directorate have ongoing programs to advance needed technologies to meet mission objectives. However, challenges exist in furthering these technologies for prospective mission needs. The 2013 Decadal found that NASA's Planetary Instrument Definition and Development Program had been very successful in initiating new instrument concepts and maturing them to low technology readiness levels (TRL).[57] However, the report also noted that a primary deficiency in past NASA planetary exploration technology programs had been an overemphasis on developing instruments to TRLs 1 through 3 at the expense of the more costly but vital mid-TRL efforts (4 to 6) necessary to bring a technology to flight readiness. This deficiency resulted in many important technological developments being abandoned, either permanently or temporarily, after they reached TRLs 3 or 4. We also noted in a December 2015 report that NASA could better align and prioritize its space technology projects with its mission goals.[58]

NASA's failure to mature technologies past TRLs 3 or 4 has resulted in a widespread "mid-TRL crisis" that has, in turn, created its own unique set of problems for flight projects. According to the National Academies, early investment in key critical technologies reduces the "cost risk" for complex projects, allowing technologies to be initiated with reduced uncertainty regarding their eventual total costs. Otherwise, when a new flight project desires to use a specific technology it must either complete the development itself, with the associated cost and schedule risk, or forgo the capability altogether.

In 2019, NASA conducted an independent Planetary Science Instrument Heritage Study that found that of the 117 PSD-developed instruments that have launched since 2000, only 35 were funded through PSD or Space Technology Mission Directorate programs without a specific associated flight project, while the remaining 82 instruments were developed as part of a flight projects' life cycle or did not require development.[59] Furthermore, as previously noted, the cost of recent PSD missions is rising dramatically. Consequently, high-cost missions attempt to reduce risks by reusing and adapting known heritage technologies. Specifically, the Instrument Heritage Study has shown that 96 of the 117 instruments (82 percent) flown since 2000 had prior flight heritage.

[57] The Planetary Instrument Definition and Development Program supports the advancement of spacecraft-based instrument technology that shows promise for use in scientific investigations on future planetary missions. The goal is to define and develop scientific instruments or components of such instruments to the point where the instruments may be proposed in response to future announcements of flight opportunity without additional extensive technology development. In response to the 2013 Decadal, NASA created the Maturation of Instruments for Solar System Exploration and Instrument Concepts for Europa Exploration programs to mature new instruments up to TRL 6 in preparation for potential flight missions. NASA recently created the Development and Advancement of Lunar Instrumentation program to support the advanced development of instruments.

The TRL is a widely used metric for measuring the readiness of new technologies or new applications of existing technologies to be incorporated into a product. TRLs are measured along a 1 to 9 scale, starting with level 1 being preliminary research of a basic concept, moving to laboratory demonstrations around level 4, and proven technology programs at level 9 where the technology is integrated into a product and successfully operated in its intended environment.

[58] NASA OIG, *NASA's Efforts to Manage Its Space Technology Portfolio* (IG-16-008, December 15, 2015).

[59] Planetary Science Instrument Heritage Study Final Report (Phase I), April 30, 2019, prepared by Aerospace Corporation for NASA Planetary Exploration Science Technology Office to study planetary instrument flight and funding heritage. Phase I of the report examined planetary instruments that have successfully flown or been infused since 2000. NASA Planetary Science Instrument Heritage Study (Phase II), December 31, 2019. Phase II of the report examined funding tasks awarded by PSD since 2003.

Even when technologies are developed past TRLs 3 or 4, there are often insufficient PSD missions available to support technology demonstration. Currently, PSD has five projects in development, only two of which—Mars 2020 and Europa Clipper—include instruments developed under stand-alone technology development programs. In addition, Mars 2020 and Psyche feature technology demonstrations.[60] In the Instrument Heritage Study, NASA tracked 276 task orders for principal investigators to further instrument development to various TRLs. While it may take more than one task order to successfully develop and demonstrate an instrument, the study found that only 40 of the task orders resulted in infusing instruments into a flight project. As a result, investigators are having to inefficiently string together multiple smaller instruments tasks to advance a technology. Instruments and technologies that are not selected must complete final development stages during early project phases, increasing cost and schedule risks.

NASA has taken the initiative to conduct flight instrument heritage and track funding result studies. However, the studies show that while even with successes in maturing instruments, the limited number of flight opportunities limits the number of instruments that can be flown. Additional focus and resources could increase the maturity of concepts and instruments so they would be more readily available for integration into future projects.

[60] Additionally, DART itself is a demonstration mission within planetary defense but is also demonstrating new propulsion technology (NASA's Evolutionary Xenon Thruster-Commercial). Prospectively, NASA is developing four missions: Dragonfly, two more Discovery missions, and the Mars Sample Return mission in the next 5 years.

LUNAR DISCOVERY AND EXPLORATION PROGRAM IS ACCEPTING UNDUE RISK IN COMMERCIAL LUNAR PAYLOAD SERVICES

The Lunar Discovery and Exploration Program (LDEP) is accepting higher risk than necessary in the Commercial Lunar Payload Services (CLPS) project because it did not establish a common interface to allow lunar payloads to integrate with the landers from selected CLPS contractors, as advised by the National Academies. Additionally, contrary to Federal Acquisition Regulations (FAR) guidelines, CLPS contracting personnel did not perform due diligence when awarding contracts to partners with risky business and financial histories and prior performance issues. Finally, NASA did not develop safety and mission assurance plans for all the awards as required by NASA policy and FAR guidelines. If not adequately addressed, these risks could result in mission failure and the loss of expensive NASA payloads and significant taxpayer investment.

Commercial Lunar Payload Services Project

The CLPS project, managed by LDEP, provides contracts to U.S. commercial entities to provide landers to deliver NASA science instruments and other payloads to the lunar surface.[61] To accomplish the task, the commercial entities are responsible for providing all end-to-end services, including the launch vehicle, spacecraft, and ground systems. LDEP is developing lunar surface payloads (and supporting orbital payloads) that address the nation's lunar exploration, science, and technology demonstration goals outlined in the 2013 Decadal and other National Academies' reports.[62] The first 13 instruments are ready-made technologies developed in-house by NASA and planned for delivery to selected CLPS contractors by early 2021. NASA also plans to co-develop the next 12 instruments in partnership with the science community.

In November 2018, NASA selected nine contractors to compete for up to $2.6 billion in indefinite-delivery, indefinite-quantity (IDIQ) contracts over the next 10 years.[63] According to contracting personnel, being eligible for a CLPS contract enables the contractors to compete for future task orders but does not guarantee the company anything more than $25,000—issued as Task Order 1—to develop a payload users' guide or technical manual for their lunar landing vehicle.

[61] LDEP manages a series of CLPS commercial contracts for lunar landing services, develops instruments, SmallSats, and rovers for the continuation of lunar science and manages operations of the Lunar Reconnaissance Orbiter.

[62] National Academies, *The Scientific Context for the Exploration of the Moon, and the NASA Strategic Knowledge Gaps* (2007).

[63] In November 2019, NASA announced the addition of five more American companies to join the pool of vendors to propose landers that can deliver heavier payloads to the Moon's surface. This addition will allow for a total of 14 participants to bid on the CLPS contracts. An IDIQ contract provides for an indefinite quantity, within stated limits, of supplies or services during a fixed period. The federal government places orders for individual requirements. Quantity limits may be stated as number of units or as dollar values. Funds for the minimum amount of the contract are applied at the time of award, and requirements above the minimum are then obligated on the contract when needed.

In May 2019, LDEP awarded Task Order 2 contracts to three vendors for instrument deliveries targeting late 2021 with a total base value of about $254 million. LDEP awarded another contract in April 2020 for approximately $76 million for an instrument delivery in late 2022. Task Order 2 included the potential for incremental incentives up to $10 million each if the contractor can launch by late 2020.[64] Based on the timeline for other projects of similar size and scope, the 19-month to 28-month timetables from award to potential launch to develop and integrate a first-time lander with the instruments, spacecraft, and launch vehicle is extremely aggressive and not likely to be met.[65] Because the CLPS delivery systems are still in development, such an aggressive schedule could result in mission delays or even failures, jeopardizing NASA's multi-million dollar investment and payloads.

NASA Lacks Common Interfaces between Instruments and Landers

NASA has not established common interfaces between the lunar payloads and landers to be provided by the CLPS contractors. These interfaces are essential to ensure the successful integration of electrical power, data communication, and thermal systems between the selected instruments and spacecraft from the time of launch through science operations on the lunar surface. The National Academies identified this issue in a 2019 report, recommending that NASA either develop a common instrument interface document or require that each commercial provider supply such a document to describe provider and payload capabilities for instrument hosting, interfaces, and means of resolving questions.[66] The National Academies also noted that NASA asked potential CLPS contractors to assume all activities necessary to safely integrate, accommodate, transport, and operate NASA payloads using contractor-provided assets in its request for proposal.[67] This is particularly challenging because the CLPS project has more than 25 possible instruments interfacing with 14 prospective vendors using varying spacecraft configurations. However, rather than providing interface guidelines, NASA relied on the selected contractors' abilities to accommodate whatever interface came with the instruments.

LDEP officials are aware of the lack of a common interface and have discussed several options to address this challenge, such as NASA-developed adapters unique to specific payloads and lander missions. For example, LDEP officials identified that Astrobotic's lander has a grid system that would require an adapter to integrate the payload onto the spacecraft expected for use. Mission-unique adapters provide a solution but at additional cost and potential development risks to tailor those adapters to selected CLPS landers. LDEP officials were unsure if this would be a NASA- or a CLPS provider-incurred cost adding additional uncertainty. Additionally, LDEP officials said they may specify the required interfaces for both the instruments and the CLPS landers in future task orders. However, LDEP will not be able to

[64] Task Order 2 incorporated incentives for early deliveries at $2.5 million for every 3-month interval before October 2021.

[65] For comparison, Lucy and Psyche, PSD's next two Discovery missions, will have a development time of about 4 years. Further, there has never been a landing on the Moon's surface by a commercial partner, a fact that calls into question the aggressive timeline.

[66] National Academies, *Review of the Commercial Aspects of NASA SMD's [Science Mission Directorate] Lunar Science and Exploration Initiative* (2019). As an example of a way to develop a common interface document, the Earth Science Division has developed a common interface guide and a related set of best practices recommending solutions to better align instruments or payloads with commercial satellites flown in low Earth orbit and those flown in geostationary Earth orbit. See NASA, Earth System Science Pathfinder, *Hosted Payload Interface Guide for Proposers* (2018).

[67] To identify a pool of potential CLPS contractors, NASA requested proposals and selected the contractors that are expected to manage all activities associated with the end-to-end delivery, including launch vehicles, lunar lander spacecraft, lunar surface systems, Earth reentry vehicles, and associated resources.

achieve its CLPS science objectives if the payloads do not interface with the CLPS lander correctly—a result that would require reduced payload performance, major redesigns, or a reevaluation of science objectives.

Despite these integration concerns, NASA intends to accelerate instrument deliveries by CLPS contractors to support the Artemis program's goal of landing humans on the Moon in 2024. We believe LDEP needs to take action to reduce integration risks and remove uncertainty for future deliveries by developing an instrument interface document common across providers. Otherwise, CLPS vehicles may face incompatible payloads and delays, especially when instruments will be developed by the science community with their own interface requirements and may not be available to easily support upcoming Artemis missions.

NASA Did Not Perform Due Diligence in Selecting Commercial Lunar Payload Services Contractors

NASA did not perform due diligence as required by the FAR in selecting three contractors for the CLPS project. Specifically, NASA contracting personnel did not obtain sufficient information to confirm the prospective contractors met FAR standards related to their past performance and ability to obtain financial resources. The FAR requires agencies to award contracts to responsible prospective contractors only. To be considered responsible, the FAR requires a prospective contractor to have adequate financial resources to perform the contract; be able to comply with the required delivery schedule; have satisfactory records of performance and integrity and business ethics; possess the necessary controls and skills, or the ability to obtain them; and possess the necessary equipment and facilities or the ability to obtain them.[68]

NASA contracting personnel claimed that they do not need to evaluate past performance because the CLPS-approved procurement strategy states past performance would provide no additional value in light of NASA's goal of awarding a maximum number of master contracts to achieve future task competition, and the fact that this is a new market in which no offeror has performed the entire requirement (e.g., landing on the Moon). Contracting personnel also relied on the contractors' affirmation of their compliance with FAR requirements. In our opinion, contracting personnel should reasonably perform due diligence when making the responsibility determinations, and should not ignore adverse information that is relevant and available pertaining to the contractors' past performance and financial status.

Of the first nine contractors selected under CLPS Task Order 1, we judgmentally selected three vendors with known occurrences of financial issues or performance problems and analyzed the Agency's selection processes to determine whether NASA performed the FAR-required due diligence.[69] We found that these companies did not meet the "responsible contractor" criteria as defined by the FAR, with each having a history of unsatisfactory performance records or a previous inability to obtain adequate financial resources to support government contracts.

68 FAR Parts 9.103, Policy, 9.104, *General standards*, and 9.105, *Obtaining Information* (2005).

69 The other six contractors NASA selected are: Astrobotic Technology, Inc.; Deep Space Systems; Draper; Intuitive Machines, LLC; Lockheed Martin Space; and Masten Space Systems, Inc. We did not perform an analysis of whether NASA had performed FAR-required due diligence with respect to these contractors.

- *Firefly Aerospace, Inc. (Firefly)*.[70] Prior to being selected for CLPS Task Order 1, Firefly had a history of nonperformance and questionable financial management on a NASA contract. Specifically, in 2017, NASA canceled a Venture Class Launch Services contract with Firefly when the contractor could not fulfill the contract terms despite NASA issuing a modification to ease the performance requirement. As a result, Firefly owed NASA $1.1 million from previously provided advance payments. Lack of funding necessitated Firefly's management to furlough its entire staff and consider selling the company. Consequently, it also caused NASA to terminate the Venture Class Launch Services contract.[71] A bankruptcy judge eventually provided NASA $1,500, or 0.14 percent, of its $1.1 million. Additionally, at the time of its selection for Task Order 1, the company was facing a lawsuit that further threatened its financial standing.[72] Contracting personnel were aware of Firefly's financial background and unsatisfactory performance issues but prioritized attracting additional participants into the pool. Furthermore, contracting personnel stated that any vendor's capabilities will be more closely scrutinized when NASA awards the delivery task orders. As such, in spite of the company's financial difficulties and non-performance issues, contracting personnel deemed Firefly eligible and included the company as part of NASA's effort to provide CLPS awards to as many participants as possible.[73] To date, Firefly remains eligible to compete for future NASA opportunities or task orders.
- *Moon Express*. Although the company managed to find new investors within days of being selected for the CLPS project in November 2018, in the year prior to its selection, Moon Express laid off roughly half its staff and halted projects after an investor backed out. Additionally, in January 2018, a U.S. District Court awarded $4.1 million in cash and equity in Moon Express to Intuitive Machines, a Houston-based company hired by Moon Express to write flight software and develop a terrestrial return vehicle for its commercial lunar transportation business.[74] Finally, a month after selection, NASA canceled a lease with Moon Express after the contractor failed to pay its rent at Kennedy Space Center. Moon Express was not selected for the CLPS Task Order 2, but it remains eligible to bid for future CLPS Task Orders.
- *Orbit Beyond Inc. (OBI)*. OBI was a newly formed U.S. company when NASA selected it as one of the nine CLPS Task Order 1 contractors and less than a year old when it was awarded a CLPS Task Order 2 contract for $97 million. Although NASA was aware that OBI relied on Axiom Research Labs (Axiom), a corporation based in India that licensed intellectual property and engineering design schematics to the contractor for its lunar lander, NASA did not anticipate that Axiom would propose a corporate restructuring that would give Axiom a majority control of OBI and all assets. Consequently, without Axiom's engineering design licensing agreement, OBI could no longer implement its proposed plan of domestic hardware production as indicated in

[70] Formerly known as Firefly Space Systems. After going bankrupt and being liquidated in March 2017, the company was renamed as Firefly Aerospace by Noosphere Ventures, who bought out the assets of the former Firefly Space Systems.

[71] In October 2015, NASA awarded Firefly a Venture Class Launch Services contract for $5.5 million to demonstrate a dedicated launch capability for smaller payloads that the Agency anticipates it will require on a recurring basis for future SmallSat and CubeSat missions. In early 2016, NASA issued a contract modification "to change the configuration from a land launch to an air launch and to revise the mission success criteria," according to a NASA procurement filing. NASA subsequently reduced the value of the Firefly contract by $2.4 million.

[72] Virgin Galactic filed a lawsuit against Firefly alleging that the company's Chief Executive Officer stole proprietary technology that he developed while working for Virgin Galactic.

[73] NASA selected 9 of 10 companies that responded to NASA's request for proposals.

[74] The jury found in favor of Intuitive Machines and awarded the company $1.1 million in cash and $2.5 million in Moon Express equity related to the flight software claim, as well as $732,000 related to its work on the terrestrial return vehicle.

the Task Order 2 award, a direct violation of NASA's contract terms and conditions. Less than 2 months after awarding the CLPS Task Order 2 award, NASA terminated its contract with OBI after the contractor severed its relationship with Axiom and notified the Agency that it would not be able to comply with the CLPS Task Order 2's delivery schedule.[75] Despite these issues, OBI remains a CLPS contract awardee and may be eligible to compete for future NASA opportunities or task orders.

By elevating the goal of broadening participation, NASA allowed contractors with poor financial and technical resources and unsatisfactory performance history to participate in the Agency's multi-billion-dollar CLPS project.

NASA Lacks Safety and Mission Assurance Plans for Two Commercial Lunar Payload Services Awards

Although required by NASA policy, the first two awards under CLPS Task Order 2 have no safety and mission assurance plans.[76] Program and project managers are responsible for the quality of their assigned products and services, including planning and budgeting for implementation of government contract quality assurance functions. NASA policy, as well as the FAR, requires program and project managers to determine whether an acquisition item is critical and complex.[77] For NASA, "critical" acquisition items are products or services whose failure poses a credible risk of loss of a mission resource valued at greater than $2 million, while "complex" items are those where quality is not immediately visible and conformance requires testing of some kind. If determined to be critical and complex, program and project managers are required to develop and implement a Program/Project Quality Assurance Surveillance Plan (PQASP) as their safety and mission assurance plan.[78] The purpose of PQASPs is to identify in a single document all contractor work operations requiring government surveillance and the specific method(s) for providing such surveillance. For example, a PQASP would typically include documentation showing a contractor's production processes, NASA's assessment of process risks, and a list of required surveillance activities.

NASA has stated that the nature of the CLPS Task Order 2 is akin to a delivery by common carrier, similar to an express cargo service, and therefore does not require a PQASP or even a risk assessment. We disagree and believe the CLPS task orders meet the "critical" criteria under NASA policy. Each task order award is valued at around $80 million, not including the instrument payload's additional value, far exceeding the policy's $2 million threshold. These task orders are also "complex," in that the finished launch vehicle and lunar lander service cannot simply be visually inspected to determine whether systems were properly integrated, will successfully land, and function as planned.

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[75] Upon learning of the CLPS Task Order 2 award, Axiom proposed a corporate restructuring that would give Axiom a majority control of OBI and all assets, which would violate NASA's contractual requirement of the U.S. domestic corporate ownership. Axiom threatened to exercise an exit clause in the intellectual property and engineering design licensing agreement, which would effectively cancel OBI's right to use any and all Axiom design data that was critical in OBI's lunar lander manufacturing.

[76] In May 2019, NASA selected three contractors for CLPS Task Order 2: Astrobotics ($79.5 million); Intuitive Machines ($77.2 million); and OBI ($97 million). The Orbit Beyond contract was terminated in July 2019. The CLPS master contract has Enclosure 1, which outlines NASA's intent to use a risk-based insight surveillance approach. NPR 8735.2B, *Management of Government Quality Assurance Functions for NASA Contracts* (August 12, 2013).

[77] NPR 8735.2B, *Management of Government Quality Assurance Functions for NASA Contracts* (August 12, 2013) and FAR Part 46.203, *Criteria for Use of Contract Quality Requirements* (2020).

[78] NPR 8735.2B.

If NASA intends to accept a high level of risk with CLPS Task Order 2, the Agency is still required to perform an assessment of risk within a PQASP. High-risk acceptance changes only the nature of the Agency's oversight and insight and still requires documenting the assessment within the PQASP authorizing and acknowledging that level of risk acceptance. Given the inexperience of the contractors with landing anything on the Moon, the current $160 million cost, and that the prospective contracts may eventually total $2.6 billion, the PQASP risk process may determine that additional safety and mission assurance oversight or insight activities are warranted. Without proper evaluation and oversight of risk, the aggressive approach of CLPS may result in significant additional risks, including mission failure and the loss of payloads.

INSUFFICIENT RESOURCES PREVENT NEAR-EARTH OBJECT OBSERVATION PROGRAM FROM MEETING GOALS

Despite increased funding and greater project capabilities of the Near-Earth Object Observations (NEOO) Program, resources are still insufficient to meet the congressional mandate of cataloging near-Earth objects (NEO). Without substantially increased funding to build a space-based infrared telescope, NASA will likely not meet the mandate until 2040—20 years after the original 2020 goal. Additionally, we identified specific instances of questionable use of grants for the construction of telescopes and operation and maintenance of an observatory where a contract would be more appropriate and would provide NASA greater oversight and the ability to minimize risks of improper spending.

Planetary Defense Program

Scientists classify comets and asteroids that pass within 28 million miles of Earth's orbit as NEOs. To protect the planet from potential asteroid impacts, in 2005, Congress enacted the George E. Brown, Jr. Near-Earth Object Survey Act, requiring NASA to detect, track, catalogue, and characterize 90 percent of the NEOs equal to or greater than 140 meters in diameter.[79] Congress set a goal that NASA complete the catalog within 15 years (2020) of the law's enactment. In addition, the U.S. National Space Policy directed the NASA Administrator, in cooperation with other federal agencies and commercial partners, "to detect, track, catalog, and characterize near-Earth objects to reduce the risk of harm to humans from an unexpected impact on our planet."[80]

In response to the congressional mandate, NASA established the NEOO Program, which since January 2016 has been managed by the Planetary Defense Coordination Office (PDCO) at NASA Headquarters. The NEOO Program funds space- and ground-based NEO discovery, tracking, and characterization efforts, while also supporting the development of future space-based NEO detection missions. In FY 2019, a new Planetary Defense Program budget line was established under the management of PDCO, for all efforts to find, track, and mitigate the potential hazards resulting from NEOs. Its portfolio includes both the NEOO Program and technology demonstrations such as DART, a mission intended to intercept an asteroid 6.6 million miles from Earth using a kinetic impactor to change the orbit of a small moon circling the asteroid Didymos (see Appendix B for project description).

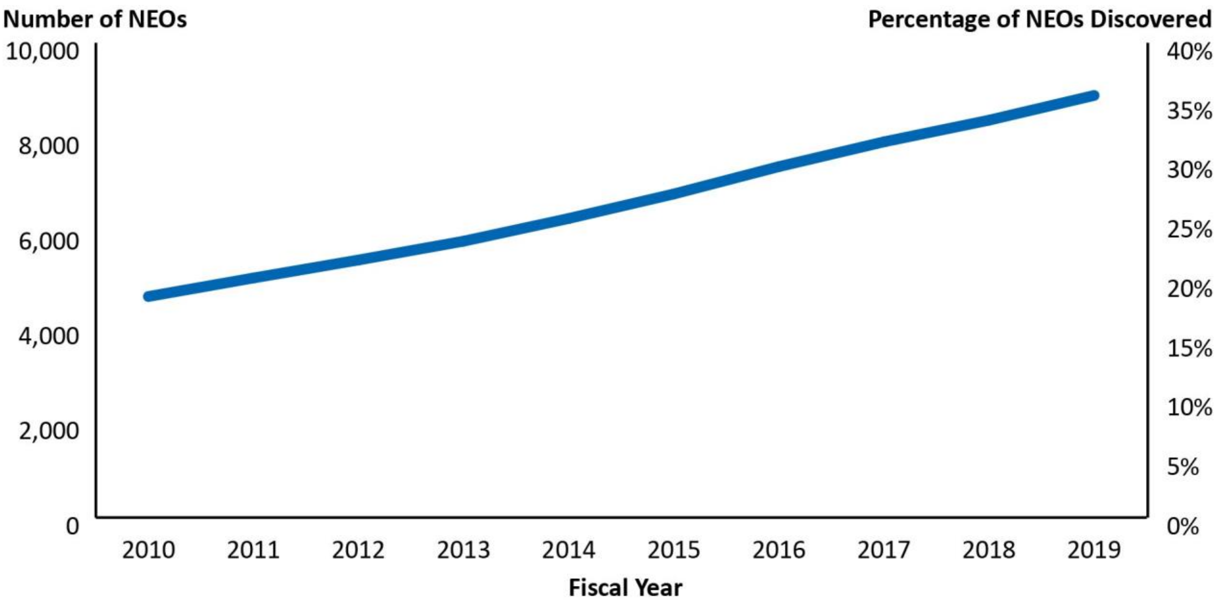
[79] Pub. L. No. 109-155, Subtitle C. An object of this size would cover an area larger than the size of three football fields laid side-by-side.

[80] *National Space Policy of the United States of America* (June 28, 2010).

NASA Will Not Meet the Congressional Mandate by 2020

NASA has not provided sufficient resources (i.e., people and funds) to enable the NEOO Program, which received $60 million in funding in FY 2019, to meet the congressional NEO mandate by 2020. Moreover, according to the National Academies, the Planetary Defense Program will not be able to set a reasonable date to reach its goals unless the Agency establishes an attainable schedule with necessary funding for the development of a space-based infrared telescope.[81] As of April 2020, about 35 percent of 140-meter or larger NEOs have been cataloged since 2005 (see Figure 7).

Figure 7: Percentage of 140-Meter or Larger Cataloged Near-Earth Objects, as of April 2020



Source: NASA OIG presentation of JPL data.

As early as 2010, the National Academies found that NASA would not meet its congressional mandate due to insufficient resources.[82] Similarly, in a September 2014 report, we found that the NEOO Program lacked a plan, adequate funding, and staffing to address the congressional mandate.[83] In response to our recommendations, in January 2016, NASA reorganized and established PDCO to oversee the NEOO Program but has not increased funding for the effort. PDCO sponsors observation projects that use a variety of NASA, National Science Foundation, and U.S. Air Force supported ground- and space-based telescopes to search for NEOs, determine their orbits, and measure their physical characteristics. The ground-based telescopes include such facilities as the Arecibo Observatory, Asteroid Terrestrial-Impact Last Alert System (ATLAS), Catalina Sky Survey, Goldstone, Infrared Telescope Facility, and the Panoramic Survey Telescope and Rapid Response System. Additionally, the aging NEOWISE space-based infrared asset assists NASA's efforts to identify and characterize the population of NEOs in a way not possible from the ground (see Appendix B for mission description). PDCO funds these activities primarily through research grants.

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[81] National Academies, *Finding Hazardous Asteroids Using Infrared and Visible Wavelength Telescopes* (2019).

[82] National Academies, *Defending Planet Earth: Near Earth Object Surveys and Hazard Mitigation Strategies* (2010).

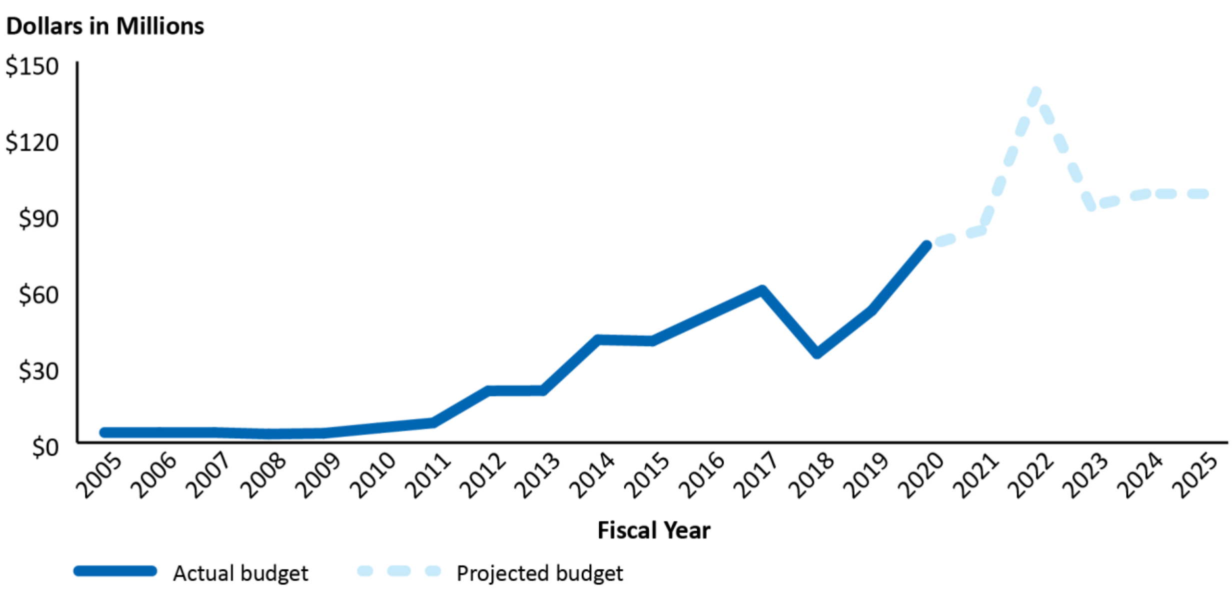
[83] NASA OIG, *NASA's Efforts to Identify Near-Earth Objects and Mitigate Hazards* (IG-14-030, September 15, 2014).

In 2018, at NASA's request, the National Academies established the Committee on Near Earth Object Observations in the Infrared and Visible Wavelengths to make recommendations about space-based telescope capabilities. The Committee's 2019 report reiterated that NASA would not accomplish the congressional mandate by 2020 with its currently available assets of ground-based telescopes and a single, soon-to-expire space-based asset.[84] According to the Committee, due to the Earth's atmosphere blocking infrared wavelengths, ground-based assets could not provide the NEOs diameter measurement and mass estimate with the same accuracy as an infrared space-based telescope. The Committee also noted that although Congress tasked NASA with NEO detection and threat characterization, it failed to provide sufficient funding to enable NASA to adequately address this task. The Committee further suggested that if NASA were to deploy a space-based infrared telescope, the congressional mandate may be accomplished within 10 years of launch.

NASA Has Consistently Underfunded the NEOO Program

Despite increases in the overall budget for the Planetary Defense Program, NASA has consistently underfunded the NEOO Program, with much of the Program's budget in recent years dedicated to developing the DART mission. For its first 6 years (FYs 2005 to 2010), the NEOO Program had a relatively small annual budget of roughly $4.2 million. From FYs 2011 to 2018, the budget steadily increased to $50 million. In FY 2019, PSD moved the NEOO Program under the newly established Planetary Defense Program and provided the Program a budget of $150 million to support both NEOO and DART project development. Of that $150 million, the NEOO Program accounted for 40 percent ($60 million) of the Planetary Defense Program's budget (see Figure 8), while the DART mission accounted for the other 60 percent ($90 million).

Figure 8: NEOO Program Budget, FYs 2005 through 2025



Source: NASA OIG presentation of NEOO Program budget information.

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[84] National Academies, *Finding Hazardous Asteroids Using Infrared and Visible Wavelength Telescopes* (2019)

According to a Planetary Defense Program official, the congressional mandate could be achieved roughly 10 years after an infrared space-based telescope known as the Near-Earth Object Surveillance Mission (NEOSM) begins flight operations. The official estimated that it would cost between $500 million and $600 million to develop NEOSM, and if the Planetary Defense Program budget were increased to about $200 million per year, NEOSM could be developed and ready for launch in roughly 4 years. This would allow NEOSM to launch by early 2026, and after collecting the necessary data, achieve the congressional mandate by 2036. However, while the FY 2020 appropriations bill provided the Planetary Defense Program with $35.6 million to start development of NEOSM, the President's FY 2021 budget request shows a budget reduction for the Program after DART is scheduled to launch in 2022. Specifically, the Program budget will decrease from $150 million in FY 2020 to less than $100 million in FYs 2023 through 2025. At that funding level, NEOSM would likely not launch until several years after the current 5-year budget plan, perhaps as late as 2030. A 2030 launch plus 10 years for data collection and cataloguing would mean that the expected completion date of the mandate would realistically be 2040 at the earliest—at least 20 years past the original goal of 2020.

Insufficient Oversight of Grantees

In FY 2019, the NEOO Program spent $40 million through contracts, grants, and task orders. Similar to a finding in our September 2014 report, we determined the PDCO spent $19 million, or nearly 50 percent, on grants that included funds not only for research and analysis but also for construction, maintenance, and operation of facilities and observatories.[85] Specifically, three grants awarded to education institutions included some funds for research but more funds for construction of facilities and observatory operations and maintenance. The Federal Grant and Cooperative Agreements Act of 1977 states "an executive agency must use a procurement contract as the legal instrument when the principal purpose of the instrument is to acquire (by purchase, lease, or barter) property or services for the direct benefit or use of the [federal government]."[86] Grants may offer greater flexibility and reduced administrative burden to NASA, but they also provide less certainty and visibility in terms of grantee performance and deliverables. A contract requires more stringent oversight of contractor costs and performance, and the contractor would have to comply with various FAR requirements.[87]

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[85] IG-14-030. In this report, we recommended and NASA agreed to "develop and implement requirements, procedures, and internal controls to address program deficiencies." In response, the Science Mission Directorate in September 2015 issued a Near Earth Object Observations Research Program Plan that, among other requirements, stated the Program follows the direction and guidance of NASA's Grant and Cooperative Agreement Handbook. The Handbook provides internal policy guidance to NASA Technical Officers and Grant Officers to implement government-wide and NASA-specific regulations for awarding and administering grants and cooperative agreements. It also includes guidance on determining the proper award types among grants, cooperative agreements, and contracts.

[86] Federal Grant and Cooperative Agreement Act of 1977, Pub. L. No. 95-224 (1978).

[87] Examples of FAR requirements that a contractor must comply with include: FAR §52.242-4, *Certification of Final Indirect Costs* (1997), whereby the contractor must certify that all submitted costs are allowable; FAR §15.406-2, *Certificate of Current Cost or Pricing Data* (2019), submitted when the contractor is required, under the Truth In Negotiations Act, to provide its backup cost data so that the contracting officer, absent price competition, can determine that the contract price is "fair and reasonable;" and FAR §52.203-2, *Certificate of Independent Pricing* (1985), where the contractor is required to certify that prices were arrived at without collusion, prices were not disclosed to competitors, and the contractor made no attempt to induce competitors not to submit offers.

In September 2018, PDCO awarded a $3.86 million, 4-year grant to the University of Hawaii System to construct two ATLAS telescopes in the southern hemisphere, extending coverage over the southern part of the sky to search for NEOs.[88] The grant contained construction costs for the ATLAS 3 and 4 telescopes, including procurement of hardware and equipment, commissioning and installation of new equipment at remote sites such as South Africa and Chile, site leases, foreign travel costs and other direct costs such as computer support, and indirect costs such as fringe benefits, payroll, and overhead costs. Compounding the issue, we found that the NASA Shared Services Center did not adequately review proposed travel costs in accordance with the Code of Federal Regulations for Grants and Agreements.[89] Specifically, the University of Hawaii System did not provide date, or purpose, nor the name and title of persons traveling or their relationship to the grantee for 16 foreign trips for a total of $66,000. In addition, the Center erroneously identified their destinations as Vienna, Austria, instead of South Africa and Chile. Though the Center reviewed the travel estimates and concluded that these trips to Vienna were reasonably priced, had this grant been a contract, in our opinion, the proposed travel costs would have undergone greater scrutiny, which would have required the contractor to better justify and support the reasonableness and allowability of the costs, in accordance with FAR requirements.[90]

Additionally, NASA OIG recently concluded an investigation that found cost mischarging related to two Universities Space Research Association grants with a total value of approximately $4 million. Although one grant involved NEO research and analysis, the other was for the operation and maintenance of the Arecibo Observatory.[91] The investigation found cost mischarging when an employee was working on one grant but charged another for this work. Because of our investigation, the Universities Space Research Association proposed credit repayments for the two grants of $131,406 and $49,118, respectively, for a full recovery of $180,524. However, despite the mischarging investigation, NASA continues to fund two other grants for the same operation and management effort of the Arecibo Observatory, except to a different grantee, the University of Central Florida.[92] The two grants, valued at $3 million and $19.2 million, respectively, were for program costs and operation and management of the observatory. Because of the funding instruments NASA chose, the Agency continues to lack visibility into the observatory's costs and does not know if the cost mischarging is a recurring issue.

[88] ATLAS provides advance warning of the imminent impact of asteroids ranging in size from 20 meters up to 140 meters. NASA funded ATLAS 1 and 2 in 2013.

[89] The NASA Shared Services Center performs selected business activities for all NASA Centers in financial management, human resources, information technology, procurement and business support services. C.F.R., Title 2,Subpart E, §200.474, *Travel Costs*, requires that if these costs are charged directly to the federal award, there must be documentation to justify (1) participation of the individual is necessary to the federal award; and (2) the costs are reasonable and consistent with non-federal entity's established travel policy.

[90] FAR 31.205-46, *Travel Costs* (2005), specifies that costs are allowable only if date and place, purpose of the trip, and name of person's and relationship to the contractors are documented.

[91] Arecibo Observatory is a National Science Foundation facility in Puerto Rico focused on radio astronomy, planetary radar, and upper atmospheric sciences. The National Science Foundation has a cooperative agreement with NASA to maintain the facility.

[92] In August 2018 and June 2019, NASA awarded 1-year and 4-year grants worth $3 million and $19.2 million, respectively, to the University of Central Florida for program costs, operations, and maintenance of the observatory. Subcontract costs under both grants were for $2 million and $11.5 million, respectively.

Though part of the awards to ATLAS and Arecibo may have supported science research, the majority of the funds were inappropriately directed to facility construction, operations, and maintenance. In our opinion, the services acquired with these grants were intended to further accomplish the congressional mandate on NEO observations, thus using contracts in these instances would have benefitted the PDCO and provided greater visibility and oversight into ATLAS and Arecibo's operations and costs as well as assurance that the level of funding and performance was consistent with contractual requirements.

We also found that NEOO Program management did not follow up in a timely manner on a grant after the Principal Investigator stopped work 1 year before the end of the grant's period of performance. The NEOO Program also did not ensure the grant was closed out and its remaining funds timely dispositioned. Specifically, NASA awarded a $160,560 grant to an astronomical society non-profit organization for a 2-year period from May 2017 to May 2019 to create software to identify asteroids and other transient and variable objects. The work was behind schedule by 9 months due to changes in staff, while the project subcontractor instructed the organization that work done under the grant was copyrighted and could not be used for the project. After 9 months spent on the grant work, the Principal Investigator alleged that the organization invoiced payment for work that was not done, along with other financial irregularities and staff payroll issues. The Planetary Defense Program did not receive any deliverable product when the Principal Investigator left the organization. NASA subsequently transferred the remaining grant fund in January 2020 to the newer institution where the Principal Investigator resides.

NASA issues grants because they offer greater flexibility and reduced administrative burden to the Agency; however, grants also provide less certainty in terms of performance and results. With the use of contracts, NASA would have greater visibility into the appropriateness of costs and more tools at its disposal to hold contractors accountable for performance.

CONCLUSION

PSD has made significant progress in meeting 2013 Decadal recommendations and is beginning to address the 2018 Midterm recommendations, particularly in the areas of implementing priority Flagship missions and funding research analysis and technology development. However, despite funding growth, the costs of missions are increasing and may adversely impact future program cadence and performance. Reduced cadence may have the secondary effect of less opportunities for advancing important technology development and training the next generation workforce. More importantly, deteriorations in support facilities such as DSN, challenges in maintaining a specialized workforce and retaining NASA unique capabilities and knowledge, and the risks associated with implementing commercial launch and delivery service, as well as delaying attainment of congressional goals associated with NEOs, will affect the future success of PSD's science portfolio and meeting National Academies' recommendations.

Recommendations, Management's Response, and Our Evaluation

To improve NASA's management of its planetary science portfolio, we recommend the Associate Administrator for Science Mission Directorate direct the PSD Director do the following:

1. Communicate to the National Academies realistic costs of planetary science missions and consider resetting the cost caps and/or the cadence of PSD missions to reflect rising mission costs.
2. In coordination with the Office of Chief Financial Officer, engage relevant Centers and technical capability leaders to identify budgetary and accounting system solutions within the current budgetary and full cost accounting system to adequately fund and sustain critical technical discipline capabilities needed to support current and future projects.
3. In coordination with the Office of the Chief Human Capital Officer, review and identify opportunities based on existing NASA leading practices to foster and monitor mentoring to ensure a robust pipeline for PSD-related disciplines.
4. In coordination with Space Communications and Navigation, complete an assessment of DSN's infrastructure in order to develop and implement a maintenance and upgrade plan to support PSD missions.
5. In coordination with the Space Technology Mission Directorate, evaluate each Directorate's respective roles in basic research that may affect PSD projects and identify opportunities to advance technologies through flight demonstrations.
6. Reassess the NEOO Program's priority in meeting the goal of cataloging 90 percent of the NEOs larger than 140 meters, establish cost and schedule estimate with proposed funding profile to meet the NEOO's goal of cataloging, and coordinate with Congress and request funding to support the implementation goal.
7. In coordination with the NASA Shared Services Center, comply with the Federal Grant and Cooperative Agreements Act of 1977 on the proper use of grants and contracts to allow Center and Program personnel greater visibility into partner operations and to ensure that funding levels and performance are commensurate with requirements.

To reduce risks with the CLPS project, we recommend the Associate Administrator for Science Mission Directorate direct the Deputy Associate Administrator for Exploration do the following:

8. Implement the National Academies recommendation to establish a common interface for CLPS contractors between instrument and spacecraft or to require that each commercial provider supply a document that describes provider and payload capabilities.
9. In coordination with CLPS contracting personnel, establish procedures for evaluation, periodic re-evaluation, and monitoring of current and prospective CLPS contractors' past performance and financial capabilities risk, and steps to mitigate those risks when applicable.

10. Comply with NASA policy to establish program/project quality assurance surveillance plans, or its intent thereof, for all applicable CLPS task orders.

To improve NASA's guidance, communications, and management controls of special hiring authorities to help fill or retain critical knowledge and disciplines, we also recommend the Chief Human Capital Officer, in coordination with Center management and technical capability leaders do the following:

11. Develop procedures for periodic communication of the available hiring authorities, including but not limited to NEX and Pathways, guidance regarding the use of hiring authorities and the tools resident on USAJOBS.gov, monitoring of usage, and identifying and reporting usage challenges to Center and senior management.

We provided a draft of this report to NASA management who concurred with our recommendations and described planned actions to address them. We consider the proposed actions responsive to our recommendations and will close the recommendations upon verification and completion of the actions.

Management's full response to our report is reproduced in Appendix C. Technical comments provided by management and revisions to address them have been incorporated as appropriate.

Major contributors to this report include Raymond Tolomeo, Science and Aeronautics Research Director; Stephen Siu, Project Manager; Scott Bruckner; Anh Doan; Sarah McGrath, and John Schultz.

If you have questions about this report or wish to comment on the quality or usefulness of this report, contact Laurence Hawkins, Audit Operations and Quality Assurance Director, at 202-358-1543 or laurence.b.hawkins@nasa.gov.

Paul K. Martin
Inspector General

APPENDIX A: SCOPE AND METHODOLOGY

We performed this audit from June 2019 through August 2020 in accordance with generally accepted government auditing standards. Those standards require that we plan and perform the audit to obtain sufficient, appropriate evidence to provide a reasonable basis for our findings and conclusions based on our audit objectives. We believe that the evidence obtained provides a reasonable basis for our findings and conclusions based on our audit objectives. The scope of this audit included PSD missions' technical objectives, performance, milestones, cost controls, and compliance with the National Academies recommendations and congressional requirements.

Our overall objective was to assess NASA's management of its planetary science portfolio and examine whether it is achieving established goals and priorities. Specifically, we determined whether the planetary science missions are achieving technical objectives, meeting milestones, controlling costs, and addressing the National Academies' recommendations and congressional requirements. We also reviewed internal controls as they relate to the overall objective.

To determine if the planetary science missions are achieving technical objectives, we interviewed PSD Headquarters officials to gain an understanding of their processes for managing science capabilities to achieve technical objectives.

To evaluate how NASA is controlling costs for PSD's missions, we reviewed FYs 2018, 2019, 2020, and 2021 budgets and actual data from the President's budget request reports for NASA as well as information provided by PSD officials and the missions' monthly status reports. We also judgmentally selected Research and Analysis and Planetary Defense grants for review.

To determine whether PSD appropriately implemented recommendations, decisions rules, and action plans provided in its governing documents, we gathered publicly available data on the status of PSD's missions. We also reviewed and analyzed recommendations made in the National Academies' 2013 Decadal and 2018 Midterm and interviewed certain members of the 2013 Decadal committee and PSD staff. We interviewed all 19 Capability Leadership Teams, but for the purpose of our audit, we treated Active Thermal as its own Capability Leadership Team/Technical Discipline Team and scoped out Life Support, which is a Human Exploration and Operations Mission Directorate focused discipline. In addition, we discussed infrastructure risks and conclusions from the Technical Capabilities Assessment Team, Capability Leadership Teams, and Technical Discipline Teams with the projects, Office of the Chief Engineer, and Office of the Chief Human Capital Officer. We limited our scope on hiring authority usage, relying instead on these reports and interviews.

To gain an understanding of NASA's planetary science portfolio, we conducted our review at Ames Research Center, Glenn Research Center, Goddard Space Flight Center, NASA Headquarters, Jet Propulsion Laboratory, Johnson Space Center, Kennedy Space Center, and Marshall Space Flight Center. We obtained and examined internal and external applicable documents related to the planetary science portfolio. Finally, we reviewed federal and NASA criteria, policies, and procedures and supporting documentation; prior audit reports; external reviews; and other documents related to the planetary science portfolio. The documents we reviewed included, but were not limited to, the following:

- Code of Federal Regulations (C.F.R.), Title 2, Vol. 1, Part 220, *Office of Management and Budget Circular A-21, Cost Principles for Educational Institutions* (2012)

- Federal Acquisition Regulations (FAR) 31.205-46, *Travel Costs* (2019)
- FAR SubPart 9.1, *Responsible Prospective Contractors*, Section 103, *Policy* (2019)
- FAR 9.104, *Standards* (2019)
- FAR 9.105, *Procedures* (2019)
- *Standards for Internal Control in the Federal Government* (GAO-14-704G, September 2014)
- *National Space Policy of the United States of America* (June 28, 2010)
- Pub. L. No. 95-224, *Federal Grant and Cooperative Agreement Act of 1977* (February 3, 1978)
- Pub. L. No. 108-201, *NASA Flexibility Act of 2004* (February 24, 2004)
- Pub. L. No. 109-155, *National Aeronautics and Space Administration Authorization Act of 2005* (December 30, 2005)
- Pub. L. No. 115-10, *National Aeronautics and Space Administration Transition Authorization Act of 2017* (March 21, 2017)
- NASA NSREF-3000-0777, *NASA Desk Guide on NASA Excepted (NEX) Employment - Processing and Benefits* (August 7, 2019)
- NASA Policy Directive (NPD) 1000.3E, *The NASA Organization with change 64* (April 15, 2015)
- NPD 3213.1, *Excepted Service Appointments* (June 1, 2016)
- NPD 7100.10F, *Curation of Institutional Scientific Collections* (May 26, 2016)
- NASA Procedural Requirements (NPR) 3300.1C, *Employment, Appointment Authorities, and Details* (November 1, 2015)
- NPR 7120.5E, *NASA Space Flight Program and Project Management Requirements w/Changes 1-18* (August 14, 2012)
- NPR 8705.6D, *Safety and Mission Assurance (SMA) Audits, Reviews, and Assessments* (March 29, 2019)
- NPR 8735.2B, *Management of Government Quality Assurance Functions for NASA Contracts* (August 12, 2013)
- NPR 9060.1A, *Accrual Accounting - Revenues, Expenses, and Program Costs* (May 2, 2016)
- NASA Shared Services NSSDG-5100-0005, *NASA Shared Services Center Service Delivery Guide* (May 1, 2018)
- *NASA Grant and Cooperative Agreement Manual* (December 26, 2014, revised August 22, 2019)
- National Academies, *An Astrobiology Strategy for the Search for Life in the Universe* (2019)
- National Academies, *Finding Hazardous Asteroids Using Infrared and Visible Wavelength Telescopes* (2019)
- National Academies, *Report Series: Committee on Astrobiology and Planetary Science: Review of the Commercial Aspects of NASA SMD's [Science Mission Directorate] Lunar Science and Exploration Initiative* (2019)

- National Academies, *Report Series: Committee on Astrobiology and Planetary Science: Review of the Planetary Science Aspects of NASA SMD's [Science Mission Directorate] Lunar Science and Exploration Initiative* (2019)
- National Academies, *The Science of Effective Mentorship in STEMM* (2019)
- National Academies, *Strategic Investments in Instrumentation and Facilities for Extraterrestrial Sample Curation and Analysis* (2019)
- National Academies, *Exoplanet Science Strategy* (2018)
- National Academies, *Visions into Voyages for Planetary Science in the Decade 2013-2022: A Midterm Review* (2018)
- National Academies, *Review of the Restructured Research and Analysis Programs of NASA's Planetary Science Division* (2017)
- National Academies, *Extending Science: NASA's Space Science Mission Extensions and the Senior Review Process* (2016)
- National Academies, *Lessons Learned in Decadal Planning in Space Science: Summary of a Workshop* (2013)
- National Academies, *Vision and Voyages for Planetary Science in the Decade 2013-2022* (2011)
- National Academies, *Opening New Frontiers in Space: Choices for the Next New Frontiers Announcement of Opportunity* (2008)
- National Academies, *Building a Better NASA Workforce: Meeting the Workforce Needs for the National Vision for Space Exploration* (2007)
- Near-Earth Objects Science Definition Team, *Update to Determine the Feasibility of Enhancing the Search and Characterization of NEOs* (September 2017)

Assessment of Data Reliability

We assessed the reliability of computer processed data by (1) performing electronic testing, (2) reviewing existing information about the data and system that produced them, and (3) comparing the information with other available supporting documents and corroborating it with PSD documents and the input of various Division officials. We determined that the data were sufficiently reliable for the purposes of this report.

Review of Internal Controls

We assessed internal controls and compliance with laws and regulations necessary to satisfy the audit objective. However, because our review was limited to these internal control components and underlying principles, it may not have disclosed all internal control deficiencies that may have existed at the time of this audit.

Prior Coverage

During the last 9 years, the NASA OIG and GAO have issued 25 reports of significant relevance to the subject of this report. Unrestricted reports can be accessed at https://oig.nasa.gov/audits/auditReports.html and http://www.gao.gov, respectively.

NASA Office of Inspector General

Management of NASA's Europa Mission (IG-19-019, May 29, 2019)

Audit of NASA's Security Operations Center (IG-18-020, May 23, 2018)

NASA's Surface Water and Ocean Topography Mission (IG-18-011, January 17, 2018)

NASA's Parts Quality Control Process (IG-17-016, March 29, 2017)

NASA's Efforts to "Rightsize" its Workforce, Facilities, and Other Supporting Assets (IG-17-015, March 21, 2017)

NASA's Management of Electromagnetic Spectrum (IG-17-012, March 9, 2017)

NASA's Mars 2020 Project (IG-17-009, January 30, 2017)

NASA's Efforts to Manage Its Space Technology Portfolio (IG-16-008, December 15, 2015)

NASA's Management of the Deep Space Network (IG-15-013, March 26, 2015)

The Science Mission Directorate's Mission Extension Process (IG-15-001, October 9, 2014)

NASA's Efforts to Identify Near-Earth Objects and Mitigate Hazards (IG-14-030, September 15, 2014)

Mars Atmosphere and Volatile Evolution (MAVEN) Project (IG-13-009, February 21, 2013)

NASA's Challenges to Meeting Cost, Schedule, and Performance Goals (IG-12-021, September 27, 2012)

NASA's Management of Moon Rocks and Other Astromaterials Loaned for Research, Education, and Public Display (IG-12-007, December 8, 2011)

NASA's Grant Administration and Management (IG-11-026, September 12, 2011)

NASA's Management of the Mars Science Laboratory Project (IG-11-019, June 8, 2011)

Government Accountability Office

NASA: Assessments of Major Projects (GAO-20-405, April 29, 2020)

NASA Lunar Programs: Opportunities Exist to Strengthen Analyses and Plans for Moon Landing (GAO-20-68, December 19, 2019)

NASA: Assessments of Major Projects (GAO-19-262SP, May 30, 2019)

Federal Workforce: Key Talent Management Strategies for Agencies to Better Meet Their Missions (GAO-19-181, March 28, 2019)

High Risk Series: Substantial Efforts Needed to Achieve Greater Progress on High-Risk Areas (GAO-19-157SP, March 6, 2019)

NASA Major Projects: Portfolio Is at Risk for Continued Cost Growth and Schedule Delays (GAO-18-576T, June 14, 2018)

NASA: Assessments of Major Projects (GAO-18-280SP, May 1, 2018)

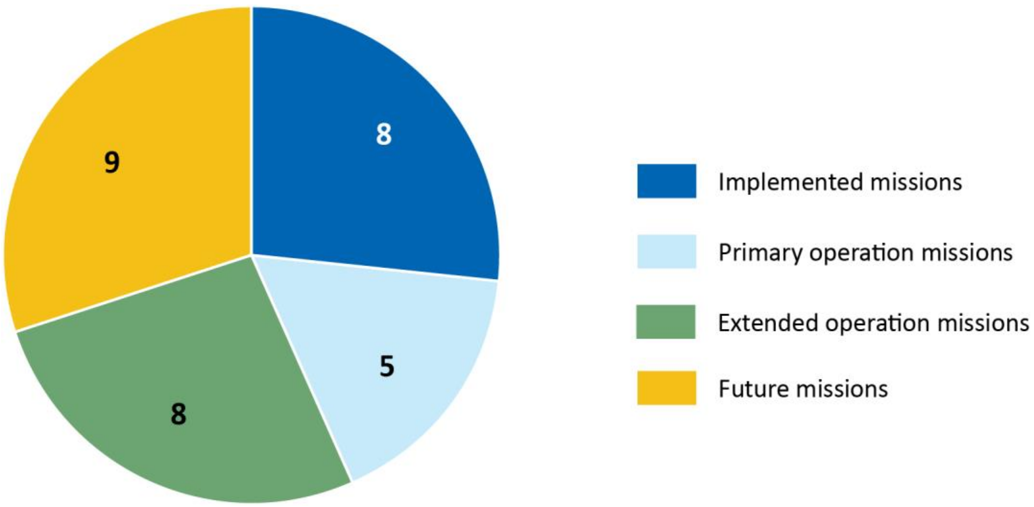
Space Exploration: DOE Could Improve Planning and Communication Related to Plutonium-238 and Radioisotope Power Systems Production Challenges (GAO-17-673, September 8, 2017)

NASA: Assessments of Selected Large-Scale Projects (GAO-12-207SP, March 1, 2012)

Appendix B: Missions in the Planetary Science Portfolio

There are 30 missions within NASA's planetary science portfolio in four different phases: implementation, primary operations, extended operations, and future (see Figure 9). This appendix provides a brief overview of these missions, including launch dates, life-cycle cost estimates, and the focus areas for each mission when available. Table 3 describes NASA's five planetary science study subject areas, their respective science goals, and the icon used to reflect each mission's study subject area and science goals in this appendix.

Figure 9: Planetary Science Portfolio Mission Breakdown



Source: NASA OIG.

Table 3: Planetary Science Study Subject Areas and Science Goals

Study Subject Area	Icon	Science Goals	Planetary Targets
Primitive Bodies		• Decipher the record in primitive bodies of epochs and processes not obtainable elsewhere • Understand the role of primitive bodies as building blocks for planets and life • Conduct planetary defense activities by characterizing near-Earth objects and mitigating potential threats	Asteroids, comets, Kuiper belt objects, possibly the Martian moons, meteorites, and interplanetary dust particles
Inner Planets		• Understand the origin and diversity of terrestrial planets • Understand how the evolution of terrestrial planets enables and limits the origin and evolution of life • Understand the processes that control climate on Earth-like planets	Mercury, Venus, and the Moon
Mars		• Determine if life ever arose on Mars • Understand the processes and history of the Martian climate • Determine the evolution of the surface and interior	Mars
Giant Planets		• Giant planets as ground truth for exoplanets • Giant planets' role in promoting a habitable planetary system • Giant planets as laboratories for properties and processes on Earth	Neptune, Uranus, Saturn, and Jupiter
Satellites of the Giant Planets		• Determine how the satellites of the outer solar system formed and evolved • Understand the processes that control the present-day behavior of these bodies • Understand the processes that result in habitable environments	Jupiter's moons (Io, Europa, Ganymede, and Callisto), Saturn's moons (Mimas, Enceladus, Tethys, Dione, Rhea, Titan, and Iapetus), Uranus' moons (Miranda, Ariel, Umbriel, Titania, and Oberon), and Neptune's moon Triton

Source: NASA OIG presentation of National Academies information.

Missions in Implementation

Double Asteroid Redirection Test

Operating Status	Launch Window	Planned Life-Cycle Costs
Implementation	July 2021	$314 million

The Double Asteroid Redirection Test (DART) will demonstrate the kinetic impact technique to change the motion of an asteroid in space. DART will deliberately crash into the asteroid at a speed of approximately 13,000 miles per hour to change the period of the orbit of the asteroid around the main body by a fraction of 1 percent. The impact will be enough to be measured using telescopes on Earth but without any detectable change to the orbit of the system about the Sun.

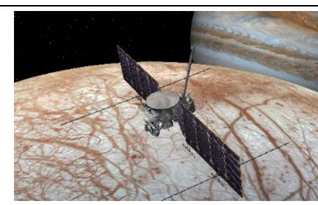
Location	Didymos binary near-Earth asteroid
Operations Platform	Probe
NASA Program	Planetary Defense
NASA Centers	NASA Headquarters (Planetary Defense Coordination Office), Glenn Research Center, Goddard Space Flight Center, Johnson Space Center, Langley Research Center, and Marshall Space Flight Center.
Non-NASA Partners	Applied Physics Laboratory (Project Management); Aerojet Rocketdyne; Auburn University; Lawrence Livermore National Laboratory; Northern Arizona University; University of Colorado, Boulder; University of Maryland; Planetary Science Institute; European Space Agency; and Agenzia Spaziale Italiana (Italy)

Science Goals	Science Benefits	
	• Demonstrate the effectiveness of the kinetic impact technique for deflecting a hazardous asteroid	• Improve our understanding of the physics involved, the effects on the small body physical dynamics, and our readiness to respond to an actual asteroid impact threat

Europa Clipper

Operating Status	Launch Window	Planned Life-Cycle Costs
Implementation	September 2025	$4.3 billion

NASA's Europa Clipper mission will send a highly capable, radiation-tolerant spacecraft to conduct detailed reconnaissance of Jupiter's moon Europa and investigate whether the icy moon could harbor conditions suitable for life. The mission will place a spacecraft in a long, looping orbit around Jupiter to perform repeated close flybys of Europa—a world that shows strong evidence for an ocean of liquid water beneath its icy crust and which could host conditions favorable for life.



Location	Jupiter (Europa)
Operations Platform	Orbiter
NASA Program	Outer Planets and Ocean Worlds
NASA Centers	Jet Propulsion Laboratory and Goddard Space Flight Center
Non-NASA Partners	Applied Physics Laboratory, Southwest Research Institute, Arizona State University, and University of Texas, Austin

Science Goals	Science Benefits	
	• Investigate Europa's habitability • Determine if Europa has the capability to support life, though the spacecraft is not designed to detect life	• Scout for sites where future spacecraft could safely land on the surface

ExoMars 2022

Operating Status	Launch Window	Planned Life-Cycle Costs[a]
Implementation	2022 (TBD)	$128 million

The 2022 mission of the ExoMars program will deliver a European rover and a Russian surface platform to the surface of Mars. The ExoMars rover will travel across the Martian surface to search for signs of life. The rover will collect samples with a drill and analyze them with next-generation instruments. ExoMars will be the first mission to combine the capability to move across the surface and to study Mars at depth. NASA's participation in the mission includes providing a mass spectrometer and key electronic components to the premier astrobiology instrument on the rover, the Mars Organic Molecule Analyzer.

Location	Mars
Operations Platform	Rover
NASA Program	Mars Exploration
NASA Centers	Jet Propulsion Laboratory and Goddard Space Flight Center
Non-NASA Partners	European Space Agency

Science Goals

Science Benefits

- Search for evidence of ancient life in the rock record (biosignatures) on Mars
- Investigate the geology and mineralogy of an ancient, clay-bearing terrane on Mars
- First deep drilling on another planet (up to 2 meters deep) to analyze samples to characterize geochemistry and water
- First use of laser desorption/ionization mass spectrometry on a planetary mission, and a powerful combination of laser desorption/ionization and gas chromatography mass spec to identify organic compounds
- Investigate subsurface geological structures
- Study of atmospheric conditions (e.g., radiation and dust)

[a] Costs are for NASA-provided Mars Organic Molecule Analyzer only.

Jupiter Icy Moons Explorer

Operating Status	Launch Window	Planned Life-Cycle Costs[a]
Implementation	May 2022	$140 million

NASA is collaborating with the European Space Agency on a mission to Ganymede and the Jupiter system. The Jupiter Icy Moons Explorer mission provides an opportunity for comparative investigation of three of the ocean worlds in the Jupiter system: Callisto, Europa, and Ganymede. The NASA contribution consists of three separate projects: one full instrument, Ultra Violet Spectrometer; sensors for the Particle Environment Package suite; and key subsystems for the Radar for Icy Moon Exploration instrument.

Location	Jupiter System
Operations Platform	Orbiter
NASA Program	Outer Planets and Ocean Worlds
NASA Centers	Instrument contributions: Jet Propulsion Laboratory
Non-NASA Partners	Southwest Research Institute, European Space Agency, Applied Physics Laboratory, Agenzia Spaziale Italiana (Italy), and Swedish National Space Agency

Science Goals

Science Benefits

- Investigate the emergence of habitable worlds around gas giants
- Characterize conditions that may have led to the emergence of habitable environments among the Jovian icy satellites
- Characterize Ganymede as a planetary object and possible habitat
- Study Callisto as a remnant of the early Jovian system
- Explore Europa's recently active zones

[a] Costs are for NASA-contributed instruments only.

Lucy		
Operating Status	**Launch Window**	**Planned Life-Cycle Costs**
Implementation	October 2021	$981 million

Lucy will be the first space mission to study the Trojan asteroids which orbit Jupiter. After launch, Lucy will complete a 12-year journey to eight different asteroids—a Main Belt asteroid and seven Trojans. Lucy's trajectory will fly-by both leading and trailing Trojan asteroid clusters and provide the first close-up view of those objects. Lucy's discoveries will open new insights into the solar system formation and origins.

Location	Jupiter (Trojans)
Operations Platform	Orbiter
NASA Program	Discovery
NASA Centers	Goddard Space Flight Center
Non-NASA Partners	Southwest Research Institute (Principal Investigator), Applied Physics Laboratory, Arizona State University; and Lockheed Martin Space Systems

Science Goals

Science Benefits

- Provide target diversity determination
- Panchromatic imaging
- Color and Near-Infrared imaging
- Mass determination
- Temperature determination

Lunar Polar Hydrogen Mapper		
Operating Status	**Launch Window**	**Planned Life-Cycle Costs**
Implementation	Artemis 1 – 2021 (TBD)	$15 million

The Lunar Polar Hydrogen Mapper, or "LunaH-Map" for short, will produce the most detailed map to date of the Moon's water deposits, unveiling new details about the depth and distribution of the ice that has been tentatively identified from previous missions. It is a CubeSat weighing about 30 pounds designed to sense the presence of hydrogen in craters and other areas on the Moon. It will embark on a 60-day science mission, consisting of 141 science orbits.

Location	Moon
Operations Platform	CubeSat
NASA Program	Discovery/Small Innovative Missions for Planetary Exploration
NASA Centers	Marshall Space Flight Center
Non-NASA Partners	Arizona State University (Principal Investigator); Tyvak Nano-Satellite Systems, Inc; Qualtec, Inc; KinetX, Inc.; AZ Space Technologies; Busek, Inc.; Blue Canyon Technologies; Radiation Monitoring Devices; Space Dynamics Laboratory; and MMA Design LLC

Science Goals

Science Benefits

- Produce detailed maps of the amount of hydrogen within the top layer of soil on the Moon
- Characterize ice deposits at the Moon's South Pole and help determine how they were created

Mars 2020 / Perseverance Rover

Operating Status	Launch Date	Planned Life-Cycle Costs
Implementation	July 2020	$2.7 billion

The Mars 2020 mission and Perseverance rover will seek signs of past life on Mars, collect and store a set of samples for potential return to Earth in the future, and test new technology to benefit future robotic and human exploration of Mars. The rover will also conduct geological assessments of its landing site to determine the potential habitability of the environment.

Location	Mars
Operations Platform	Rover
NASA Program	Mars Exploration
NASA Centers	Jet Propulsion Laboratory
Non-NASA Partners	Arizona State University; Los Alamos National Laboratory; Massachusetts Institute of Technology; Centre National d'Etudes Spatiales (France); Norwegian Defense Research Establishment (Norway); and Centro de Astrobiologia, Instituto Nacional de Tecnica Aeroespacial (Spain)

Science Goals

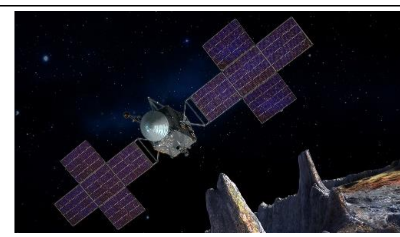
Science Benefits

- Investigate habitable environments, including an ancient lakebed, river system, and delta, on Mars
- Search for evidence of ancient life in the rock record (biosignatures) on Mars
- Characterize the chemistry, texture, and mineralogy of materials on the surface of Mars at the microscopic scale
- Determine the subsurface structure of geological features on Mars to 100 meter depth
- Prepare a cache of Martian materials (rocks and sediment) for return to Earth for detailed study
- Study atmospheric conditions (e.g., radiation, dust and use of atmospheric gases) to prepare for human exploration

Psyche

Operating Status	Launch Window	Planned Life-Cycle Costs
Implementation	August 2022	$996 million

The Psyche mission will explore a giant metal asteroid in the Main Asteroid Belt that orbits between Mars and Jupiter. Scientists wonder whether Psyche could be an exposed core of an early planet that could have been as large as Mars, but which lost its rocky outer layers due to a number of violent collisions billions of years ago.



Location	Psyche asteroid
Operations Platform	Orbiter
NASA Program	Discovery
NASA Centers	Jet Propulsion Laboratory
Non-NASA Partners	Arizona State University (Principal Investigator), Applied Physics Laboratory, Maxar Technologies, and Technical University of Denmark

Science Goals

Science Benefits

- Understand a previously unexplored building block of planet formation
- Explore a new type of world. For the first time, examine a world made not of rock or ice, but of metal.
- Look inside the terrestrial planets, including Earth, by directly examining the interior of a differentiated body, which otherwise could not be seen

Missions in Operation

BepiColombo		
Operating Status	**Launch Date**	**Planned Life-Cycle Costs[a]**
Primary	October 2018	$34 million

Due to arrive in December 2025, BepiColombo is an international mission from the European Space Agency and Japan Aerospace Exploration Agency riding together to orbit and study Mercury, the least explored planet in the inner Solar System. The mission is comprised of two spacecraft: Mercury Planetary Orbiter, which will map the planet, and the Mercury Magnetospheric Orbiter that will investigate Mercury's magnetic field. The mission will study the planet's composition, geophysics, atmosphere, magnetic field, and history. NASA provided a mass spectrometer that will determine the chemical composition of Mercury's surface.

Location	Mercury
Operations Platform	Orbiters
NASA Program	Discovery
NASA Centers	Marshall Space Flight Center
Non-NASA Partners	European Space Agency, Japanese Aerospace Exploration Agency, and Southwest Research Institute

Science Goals

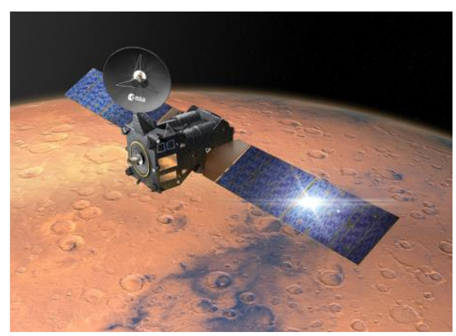
Science Benefits

- Investigate the composition, geophysics, atmosphere, magnetic field, and history of Mercury
- Map the planet
- Investigate the composition, structure, and dynamics of Mercury's very thin atmosphere using NASA's 'Strofio' instrument
- Study the Sun and the space-weather environment of the innermost Solar System during mission's cruise phase and the prime Mercury orbital mission
- Perform two Venus 'flybys' as it travels to Mercury, during which there will be the opportunity to study Venus, including its atmosphere and climate

[a] Costs are for the NASA-contributed mass spectrometer.

ExoMars 2016		
Operating Status	**Launch Date**	**Planned Life-Cycle Costs[a]**
Primary	March 2016	$36 million

The ExoMars program is a series of two missions designed to understand if life ever existed on Mars. The first mission in the ExoMars program is the ExoMars Trace Gas Orbiter launched in March of 2016. For this mission, NASA contributed two Electra ultra-high frequency telecommunication radios that act as a communications relay and navigation aid for the European Space Agency's landers and rovers.



Location	Mars
Operations Platform	Orbiter
NASA Program	Mars Exploration
NASA Centers	Radios contributed by Jet Propulsion Laboratory
Non-NASA Partners	European Space Agency

Science Goals

Science Benefits

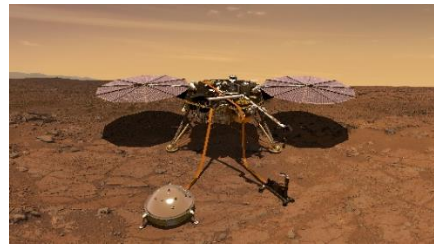
- Observations of key atmospheric trace gases, as indicators of atmospheric photochemistry and of exchange with the Martian surface, as indicators of possible geobiochemistry
- Possible detection of signs of subsurface microbial life

[a] Costs are for NASA contributions only.

Interior Exploration using Seismic Investigations, Geodesy and Heat Transport

Operating Status	Launch Date	Planned Life-Cycle Costs
Primary	May 2018	$829 million

The Interior Exploration using Seismic Investigations, Geodesy and Heat Transport (InSight) is a robotic lander designed to study the interior of the planet Mars. InSight's science instruments will take precise measurements of quakes and other internal activity on Mars to help understand the planet's history and structure and provide precise measurements of planetary rotation.



Location	Mars
Operations Platform	Lander
NASA Program	Discovery
NASA Centers	Jet Propulsion Laboratory
Non-NASA Partners	Centre National d'Etudes Spatiales (France) and Deutsches Zentrum für Luft- und Raumfahrt (Germany)

Science Goals

Science Benefits

- Provides our first look into the deep interior of Mars by mapping the planet's crust, mantle, and core to help determine the processes that created the planets during the earliest days of the solar system
- Understand how planets become habitable or not, and to better understand the birth and evolution of Earth

Juno

Operating Status	Launch Date	Planned Life-Cycle Costs
Primary	August 2011	$1.1 billion

Since arrival in July 2016, the Juno orbiter is conducting an in-depth study of Jupiter, the most massive planet in the solar system. Juno is sampling Jupiter's full range of latitudes and longitudes. From its polar perspective, Juno combines remote sensing observations to explore the polar magnetosphere and determine what drives Jupiter's remarkable auroras. Juno is currently in a 53-day orbit and has successfully completed more than half of its primary mission science flybys.

Location	Jupiter
Operations Platform	Orbiter
NASA Program	New Frontiers
NASA Centers	Jet Propulsion Laboratory and Marshall Space Flight Center
Non-NASA Partners	Southwest Research Institute (Principal Investigator), Agenzia Spaziale Italiana (Italy), University of Iowa; Applied Physics Laboratory, Centre Spatial de Liège (Belgium), and Centre National d'Etudes Spatiales (France)

Science Goals

Science Benefits

- Determine how much water is in Jupiter's atmosphere, which helps determine which planet formation theory is correct (or if new theories are needed)
- Look deep into Jupiter's atmosphere to measure composition, temperature, cloud motion, and other properties
- Map Jupiter's magnetic and gravity fields, revealing the planet's deep structure
- Explore and study Jupiter's magnetosphere near the planet's poles, especially the auroras—Jupiter's northern and southern lights—providing insights about how the planet's magnetic force field affects its atmosphere

Origins Spectral Interpretation Resource Identification and Security-Regolith Explorer

Operating Status	Launch Date	Life-Cycle Costs
Primary	September 2016	$1.1 billion

The Origins Spectral Interpretation Resource Identification and Security-Regolith Explorer (OSIRIS-REx) will be the first U.S. mission to bring a sample from an asteroid back to Earth. The OSIRIS-REx spacecraft arrived at Bennu, a near-Earth carbonaceous asteroid, in December 2018, to study the asteroid in detail and bring a sample (about 2.1 ounces) back to Earth. This mission will also measure the effect of the Sun's force on a potentially hazardous asteroid and measure the asteroid properties that contribute to this effect.

Location	Bennu Asteroid
Operations Platform	Sample Return
NASA Program	New Frontiers
NASA Centers	Goddard Space Flight Center
Non-NASA Partners	University of Arizona (Principal Investigator); Arizona State University; Denver/KinetX Aerospace; Lockheed Martin Space Systems; MacDonald, Dettwiler, and Associates Ltd.; and Massachusetts Institute of Technology

Science Goals

Science Benefits

- Return and analyze a sample of pristine carbonaceous asteroid regolith
- Provide ground truth for telescopic data of the entire asteroid population
- Map the chemistry and mineralogy of a primitive carbonaceous asteroid
- Measure the Yarkovsky effect on a potentially hazardous asteroid
- Document the regolith at the sampling site at the sub-centimeter scale

Missions in Extended Operations

Lunar Reconnaissance Orbiter

Operating Status	Launch Date	Life-Cycle Costs[a]
Extended	June 2009	$218 million

The Lunar Reconnaissance Orbiter (LRO) is a robotic mission that set out to map the Moon's surface. After a year of exploration, the mission was extended with a unique set of science objectives. With its suite of seven instruments, LRO observations have enabled numerous groundbreaking discoveries, creating a new picture of the Moon as a dynamic and complex body. These developments have set up a scientific framework through which to challenge and improve our understanding of processes throughout the solar system.

Location	Moon
Operations Platform	Orbiter
NASA Program	Lunar Discovery and Exploration
NASA Centers	Goddard Space Flight Center
Non-NASA Partners	Arizona State University; University of New Hampshire; Applied Physics Laboratory; Boston University; University of California, Los Angeles; Southwest Research Institute; Russian Institute for Space Research; and U.S. Naval Air Warfare Center

Science Goals

Science Benefits

- Create high-resolution images and maps of the surface
- Characterize the lunar radiation environment
- Identify cold traps and potential ice deposits as well as rough terrain, rock abundance, and other landing hazards
- Search for surface ice and frost in the polar regions
- Create high-resolution maps of hydrogen distribution
- Measure the slope of potential landing sites and surface roughness

[a] These are Science Mission Directorate-incurred costs only. This mission was developed under the former Exploration Systems Mission Directorate before transferring to the Science Mission Directorate.

Mars Express

Operating Status	Launch Date	Life-Cycle Costs[a]
Extended	June 2003	$76 million

Currently in its sixth extended mission operations phase, Mars Express is a European Space Agency-led mission that seeks to provide an understanding of Mars as a "coupled" system: from the ionosphere and atmosphere down to the surface and sub-surface. NASA contributed components for the Mars Advanced Radar for Subsurface and Ionospheric Sounding instrument and Analyzer of Space Plasmas and Energetic Atoms instrument and participates in the scientific analysis of mission data.

Location	Mars
Operations Platform	Orbiter
NASA Program	Mars Exploration
NASA Centers	Jet Propulsion Laboratory
Non-NASA Partners	European Space Agency and Southwest Research Institute

Science Goals

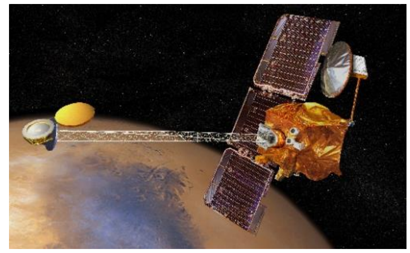
Science Benefits

- Understand what geological structures and minerals on Mars might have been formed by water
- Analyze the extent of subsurface water
- Investigate what the atmosphere can tell us about the modern Martian climate and how much water might have been lost to space in the past

[a] Costs are for NASA contributions only.

Mars Odyssey		
Operating Status	**Launch Date**	**Life-Cycle Costs**
Extended	April 2001	$627 million

Currently in its eighth extended mission operations phase, Mars Odyssey is NASA's longest-lasting spacecraft at Mars. Its primary mission included making the first global map of the amount and distribution of many chemical elements and minerals that make up the Martian surface. The mission continues to send information about Martian geology, climate, and mineralogy and additionally, provides a communication relay for robots on the Martian surface.



Location	Mars
Operations Platform	Orbiter
NASA Program	Mars Exploration
NASA Centers	Jet Propulsion Laboratory and Johnson Space Center
Non-NASA Partners	University of Arizona, Arizona State University, and Lockheed Martin Astronautics

Science Goals

Science Benefits

- Mapping of atmospheric aerosols, atmospheric mineralogy, and thermophysical properties (heat capacity, surface cohesion) of the surfaces of Mars and its moon Phobos
- Understanding the origins of the Martian moons and discoveries of hydrogen indicating water at the poles

Mars Atmosphere and Volatile Evolution		
Operating Status	**Launch Date**	**Life-Cycle Costs**
Extended	November 2013	$637 million

Orbiting Mars since 2014, the Mars Atmosphere and Volatile Evolution (MAVEN) is the first mission devoted to studying Mars' upper atmosphere, with the most comprehensive measurements ever taken to address key scientific questions about Mars' evolution. MAVEN is exploring the planet's upper atmosphere, ionosphere, interactions with the Sun and solar wind, and the resulting loss of gas from the atmosphere to space. MAVEN has been carrying out relay activities at a low level.

Location	Mars
Operations Platform	Orbiter
NASA Program	Mars Exploration
NASA Centers	Goddard Space Flight Center
Non-NASA Partners	University of Colorado (Principal Investigator) and University of California at Berkeley

Science Goals

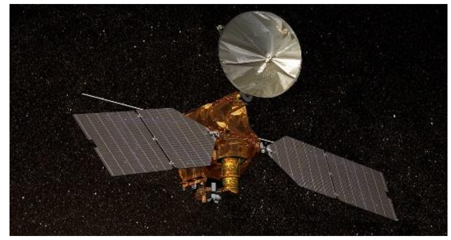
Science Benefits

- Characterization of atmospheric loss mechanisms today and their possible action over Mars history, including the fate of the ancient atmosphere
- Provides knowledge of just how Earth-like the ancient Mars climate might have been and what happened to the Mars atmosphere

Mars Reconnaissance Orbiter

Operating Status	Launch Date	Life-Cycle Costs
Extended	August 2005	$1.0 billion

In orbit since 2006 and currently on its fourth extended mission, the Mars Reconnaissance Orbiter (MRO) has studied the Red Planet's atmosphere and terrain from orbit since 2006 and serves as a key data relay station for other Mars missions. A large orbiter, it is carrying six instruments that have mapped most of the Martian surface and revealed subsurface water ice for future exploration. Additional investigations have included studies of the Martian climate, weather, atmosphere, and geology. MRO has sent images of the Martian surface that are helping scientists learn more about Mars, including the history of water flows on or near the planet's surface.



Location	Mars
Operations Platform	Orbiter
NASA Program	Mars Exploration
NASA Centers	Jet Propulsion Laboratory
Non-NASA Partners	Agenzia Spaziale Italiana (Italy), Malin Space Science Systems, Ball Aerospace & Technologies, and Applied Physics Laboratory

Science Goals

Science Benefits

- Performs daily global observation of atmospheric fields, subsurface ice detection and crustal structure, together with the highest resolution survey of surface morphology and composition
- Provides an understanding of the modern Mars environment and how it changes as well as landing site selection information for future landers

Mars Science Laboratory / Curiosity Rover

Operating Status	Launch Date	Life-Cycle Costs
Extended	November 2011	$2.5 billion

The Mars Science Laboratory (MSL) mission and its Curiosity rover successfully landed on the Martian surface in August 2012. Curiosity was designed to assess whether Mars ever had an environment able to support small life forms called microbes. In other words, its mission is to determine the planet's "habitability." Currently on its third extended mission, Curiosity has traveled more than 13 miles and continues to explore and quantitatively assess regions on Mars as potential past habitats for life, and has determined that Mars, at least at one point in time, was once able to support microbial life.

Location	Mars
Operations Platform	Rover
NASA Program	Mars Exploration
NASA Centers	Jet Propulsion Laboratory, Goddard Space Flight Center, and Ames Research Center
Non-NASA Partners	U.S. Department of Energy and international partners, including Canada, France, Spain, and Russia

Science Goals

Science Benefits

- Determine whether Mars could have supported microbial life, including the nature and inventory of organic compounds
- Assess the long-term evolution of Mars atmosphere and the present climate
- Determine the geologic history of Gale crater, including the investigation of the aqueous mineral assemblages recording the transition as Mars became the cold dry planet of today
- Characterize the full spectrum of radiation at the surface of Mars

NEOWISE

Operating Status	Launch Date	Life-Cycle Costs[a]
Extended	December 2009	$38 million

The NEOWISE project is the asteroid-hunting and characterization portion of the Wide-field Infrared Survey Explorer (WISE) mission. WISE's initial mission was to survey the full sky in infrared wavelength until the spacecraft was placed into hibernation in February 2011. In September 2013, NEOWISE was brought out of hibernation to learn more about the population of NEOs and comets that could pose an impact hazard to the Earth. The mission uses a 40-centimeter (16-inch) diameter infrared telescope in Earth-orbit to continue an all-sky astronomical survey. It is currently on its 12th full sky survey.

Location	Asteroids
Operations Platform	Surveyor
NASA Program	Planetary Defense
NASA Centers	Jet Propulsion Laboratory
Non-NASA Partners	University of Arizona (Principal Investigator), Utah State University, and Ball Aerospace and Technologies Corporation

Science Goals

Science Benefits

- Detect and characterize NEOs, providing robust estimates of their sizes and visible albedos
- Improve constraints on the population of asteroids that are low in relative velocity and therefore likely potentially hazardous
- Determine regolith properties (e.g., distinguishing between bare rock, rubble, or dusty surfaces) for objects with additional data derived from ground-based telescopes
- Discover new NEOs, some of which will be potentially hazardous asteroids and accessible to exploration

[a] This mission was developed by the Astrophysics Division. The cost amount shown is the amount of PSD funding for NEOWISE.

New Horizons

Operating Status	Launch Date	Life-Cycle Costs
Extended	January 2006	$720 million

Successfully encountering Pluto in July 2015, this mission is the first scientific investigation to obtain a close look at Pluto and its moons. Scientists aim to find answers to basic questions about the surface properties, geology, interior makeup, and atmospheres on these bodies. Now in its extended mission phase, the spacecraft ventured deeper into the Kuiper Belt and studied one of the small, and most primitive, icy bodies in this region—officially named Arrokoth—approximately two billion miles beyond Pluto's orbit, passing the body on New Year's Day, 2019.

Location	Pluto
Operations Platform	Probe (Flyby)
NASA Program	New Frontiers
NASA Centers	Goddard Space Flight Center and Jet Propulsion Laboratory
Non-NASA Partners	Applied Physics Laboratory (Project Management); Southwest Research Institute (Principal Investigator); KinetX, Inc.; Ball Aerospace Corporation; The Boeing Company; Stanford University; Lockheed Martin Corporation; University of Colorado, Boulder; and the U.S. Department of Energy

Science Goals

Science Benefits

- Flyby, characterize, and map the Pluto-Charon system as well as one or more Kuiper Belt Objects
- Provide valuable insights into the origin and evolution of planet-satellite systems, of the outer solar system, and of the ancient solar nebula
- Provide valuable insights into the comparative geology, geochemistry, tidal evolution, atmosphere and volatile transport mechanics of icy worlds

Future Missions

The following nine missions are future missions that either have not been selected yet or are in Pre-Formulation or early stages of Formulation and therefore do not yet have a launch date or estimated fully committed life-cycle cost (see Table 4).

Table 4: Future Planetary Science Missions

Mission	Phase	Program
Europa Lander	Pre-Formulation	Outer Planets and Ocean Worlds
Mars Sample Return	Pre-Formulation	Mars Exploration
Dragonfly	Formulation	New Frontiers
Commercial Lunar Payload Services[a]	Formulation	Lunar Discovery and Exploration Program (LDEP)
Martian Moons Explorer	Formulation	Discovery
Volatiles Investigating Polar Exploration Rover	Formulation	LDEP
Janus	Formulation	Discovery/Small Innovative Missions for Planetary Exploration
Lunar Trailbrazer	Formulation	Discovery/Small Innovative Missions for Planetary Exploration
NEO Surveillance Mission	Formulation	Planetary Defense

Source: OIG presentation of NASA information.

[a] The Commercial Lunar Payload Services project provides contracts to U.S. commercial entities to deliver science instruments and other payloads to the surface of the moon. For simplicity, we are counting this as one mission in this table since all of the selected spacecraft all fall under one overall indefinite-delivery, indefinite-quantity contract.

APPENDIX C: MANAGEMENT'S COMMENTS

National Aeronautics and
Space Administration

Headquarters
Washington, DC 20546-0001

Reply to Attn of: Science Mission Directorate

TO: Assistant Inspector General for Audits

FROM: Associate Administrator for Science Mission Directorate

Deputy Assistant Administrator for the Office of Human Capital Management

SUBJECT: Agency Response to OIG Draft Report, "NASA's Planetary Science Portfolio" (A-19-013-00)

NASA appreciates the opportunity to review and comment on the Office of Inspector General (OIG) draft report entitled, "NASA's Planetary Science Portfolio" (A-19-013-00), dated August 3, 2020.

In the draft report, the OIG assessed NASA's management of its planetary science portfolio and examined whether NASA's Planetary Science Division (PSD) is meeting established goals and priorities. Specifically, the OIG evaluated whether the planetary science portfolio is (1) addressing the National Academies' recommendations, (2) maintaining and enhancing its infrastructure including workforce, support facilities, and technology, (3) achieving technical objectives, and (4) satisfying congressional requirements. To complete this work, OIG interviewed PSD and other NASA officials; reviewed the status of PSD missions; and reviewed relevant Federal and NASA policies and procedures. In the draft report, the OIG makes 10 recommendations to the Associate Administrator for the Science Mission Directorate (AA/SMD) and one to the Chief Human Capital Officer (OCHCO) designed to improve NASA's management of its planetary science portfolio.

Specifically, the OIG recommends the following:

Recommendation 1: Communicate to the National Academies realistic costs of planetary science missions and consider resetting the cost caps and/or the cadence of PSD missions to reflect rising mission costs.

> **Management's Response:** NASA concurs with this recommendation. The Science Mission Directorate's Planetary Science Division has already begun a dialog with the community through the Planetary Advisory Committee and other public opportunities to

openly talk about the total actual costs of Discovery and New Frontiers missions, given the other significant components of total mission life-cycle cost over and above the development costs that are capped by the Announcement of Opportunities (AO). More importantly, future discussions will include recommendations on whether or not this paradigm needs to be changed going forward. NASA considers this a very important topic and intends for it to be discussed, in detail, at the first opportunity with the National Academies' Planetary Science Decadal Survey Committees.

Estimated Completion Date: December 31, 2020.

Recommendation 2: In coordination with the Office of Chief Financial Officer, engage relevant Centers and technical capability leaders to identify budgetary and accounting system solutions within the current budgetary and full cost accounting system to adequately fund and sustain critical technical discipline capabilities needed to support current and future projects.

Management's Response: NASA concurs with this recommendation. NASA is pleased that the OIG supports its continued implementation of full-cost accounting. NASA is faced with extremely limited and declining resources for mission support, which is responsible for funding the majority of these capabilities. NASA will evaluate where any changes towards its management decision making process, which determines the allocation of available funding for such capabilities, are warranted. In doing so, NASA will engage, where appropriate, with relevant Centers and technical capability leaders.

Estimated Completion Date: November 30, 2021.

Recommendation 3: In coordination with the Office of the Chief Human Capital Officer, review and identify opportunities based on existing NASA leading practices to foster and monitor mentoring to ensure a robust pipeline for PSD-related disciplines.

Management's Response: NASA concurs with this recommendation. NASA's PSD already has several programs aimed at fostering the development of future NASA scientists and engineers. Programs such as the Future Investigators in NASA Earth and Space Science and Technology (FINESST) program, which supports graduate students in planetary science, and Robotics Alliance, which engages high school students to gain hands-on experience and mentoring in science and engineering, have been successful at inspiring and training the next generation of engineers. PSD also supports NASA Postdoctoral Program Fellows at the NASA Centers. A network of mentors exists currently at the Agency, with Centers having local mentoring initiatives. OCHCO will provide a point of contact to work with the Planetary Science discipline lead to ensure access to mentoring resources and to assist with identification of mentoring challenges and/or requirements that may be unique to this discipline area. Additionally, the Science Mission Directorate has initiated an Agency-wide study to provide insight into the varied science career paths that exist within the Agency and outline the associated development and readiness needs for key positions within these paths. This study, to be completed by the end of 2020, will then be used to inform the development of a Web-based communications tool, to be completed by the end of FY21, to share science career path information broadly, both inside and outside of NASA.

Estimated Completion Date: September 30, 2021.

Recommendation 4: In coordination with Space Communications and Navigation, complete an assessment of DSN's infrastructure in order to develop and implement a maintenance and upgrade plan to support PSD missions.

Management's Response: NASA concurs with this recommendation. The Deep Space Network (DSN) annually produces a roadmap that includes plans for new antennas, capability updates, and obsolescence work. The obsolescence work is further defined in the DSN long term maintenance plan. SCaN will work with SMD to align this roadmap to ensure current and future PSD missions will be fully supported. The alignment of plans will be reviewed at the end of the calendar year at the SCaN Board of Directors (chaired by the Associate Administrator/SMD and HEOMD) meeting currently scheduled for December 18, 2020.

In addition, NASA recognizes that reductions to the SCaN budget and no adjustment for inflation continue to present major challenges to SCaN that may impact the DSN future readiness to meet evolving mission requirements. As such, the architecture is being reviewed constantly to ensure availability of more than adequate capacity to meet future requirements. Additionally, SCaN prioritizes critical upgrades based on Agency needs. In order to ensure there is no misalignment in stakeholder needs (and need dates), SCaN staff meets regularly with SMD and HEO stakeholders. The SCaN Board of Directors meetings further ensure concurrence with senior Agency stakeholders with Board members from Science Mission Directorate (SMD), Human Exploration and Operations Mission Directorate (HEO), Space Technology Mission Directorate (STMD), Office of Chief Engineer, Office of Chief Information Officer, and others. This coordination allows for the ability to redirect quickly based on Agency priorities.

Estimated Completion Date: December 31, 2020.

Recommendation 5: In coordination with the Space Technology Mission Directorate, evaluate each Directorate's respective roles in basic research that may affect PSD projects and identify opportunities to advance technologies through flight demonstrations.

Management's Response: NASA concurs with this recommendation. The SMD PSD works directly with the SMD Chief Technologist, who is engaged in discussions with STMD about coordinating technology investments between the two Directorates. PSD routinely describes needed technologies to STMD for use in their solicitations and also participates in reviews to select and/or continue STMD-sponsored technology development, providing feedback about relevance to PSD needs. PSD offers STMD-developed technologies to be considered as Technology Demonstration Opportunities (TDOs), resulting most recently in the inclusion of the deep space optical communications technology on Psyche. Four STMD technologies were described to the newest four Discovery mission Principle Investigators (PIs), to encourage their use as TDOs. PSD works with STMD to add new technologies when opportunities arise, with the most recent examples being the extreme environment solar power system that will fly on the Double Asteroid Redirection Test (DART) mission. Furthermore, PSD works with STMD to disseminate the results of STMD test data and lessons-learned to PSD missions that are using similar new technology.

Per the recommendation, PSD will continue to work with STMD to identify areas of collaboration, particularly through flight demonstrations. As such, PSD is planning to participate in STMD's strategic technology planning exercise, which is scheduled to be complete by 2QFY21.

Estimated Completion Date: March 31, 2021.

Recommendation 6: Reassess the NEOO Program's priority in meeting the goal of cataloging 90 percent of the NEOs larger than 140 meters, establish cost and schedule estimate with proposed funding profile to meet the NEOO's goal of cataloging, and coordinate with Congress and request funding to support the implementation goal.

Management's Response: NASA concurs with this recommendation. The PSD's Planetary Defense Program now has a flight project in formulation called the Near-Earth Object (NEO) Surveillance Mission which will develop and deliver to orbit the National Academies' recommended space-based infrared NEO survey telescope and related data analysis capability to achieve the goal of cataloging 90 percent of the NEOs larger than 140 meters within 10 years after start of its on-orbit operations. The System Requirements Review (SRR)/ Mission Definition Review (MDR) life-cycle review for this flight project will be conducted by the end of September 2020, and it is anticipated the project will complete its KDP-B milestone by the end of calendar year 2020. The pace of development and the launch readiness date will be determined by the appropriated funding provided to the program. Budget plans are being pursued to enable the program to achieve a launch readiness date as early as 2026.

Estimated Completion Date: March 1, 2021.

Recommendation 7: In coordination with the NASA Shared Services Center, comply with the Federal Grant and Cooperative Agreements Act of 1977 on the proper use of grants and contracts to allow Center and Program personnel greater visibility into partner operations and to ensure that funding levels and performance are commensurate with requirements.

Management's Response: NASA concurs with this recommendation. NASA's PSD works closely with the Senior Advisor for Research and Analysis (SARA) and other Directorate staff to ensure that appropriate funding vehicles are used and going forward will engage with the OCFO and NASA Shared Services Center (NSSC) early in the process of new awards, as appropriate, to ensure full compliance with Federal regulations. To begin this effort, PSD research and NSSC intend to conduct a review by the second quarter of FY21 with relevant staff from supporting offices to collaborate on potential improvements to the existing process and establish early touch points for future awards.

Estimated Completion Date: March 31, 2021.

To reduce risks with the CLPS project, the OIG recommends the Associate Administrator for Science Mission Directorate direct the Deputy Associate Administrator for Exploration do the following:

Recommendation 8: Implement the National Academies recommendation to establish a common interface for CLPS contractors between instrument and spacecraft or to require that each commercial provider supply a document that describes provider and payload capabilities.

Management's Response: NASA concurs with this recommendation. To better with the recommendation of the National Academies, NASA will ask each Commercial Lunar Payload Services (CLPS) commercial supplier to update their documentation of payload accommodation capabilities and interfaces. CLPS currently defines payload interfaces in each Request for Task Order Proposal, ensuring that vendors can accommodate payloads. SMD will work to ensure payload interface definitions are mature. Future payload calls may identify preferred interfaces and will encourage use of common interfaces that experience has shown all vendors already support.

Estimated Completion Date: June 30, 2021.

Recommendation 9: In coordination with CLPS contracting personnel, establish procedures for evaluation, periodic re-evaluation, and monitoring of current and prospective CLPS contractors' past performance and financial capabilities risk, and steps to mitigate those risks when applicable.

Management's Response: NASA concurs with this recommendation. NASA will document processes for evaluating past performance and financial health in task order awards.

Estimated Completion Date: June 30, 2021.

Recommendation 10: Comply with NASA policy to establish program/project quality assurance surveillance plans, or its intent thereof, for all applicable CLPS task orders.

Management's Response: NASA concurs with this recommendation. NASA will review and update the current CLPS Quality Assurance Surveillance Plan. This will inform future solicitations, as NASA will request additional information on company Safety and Mission Assurance (S&MA) approaches. Additionally, SMD will document its risk philosophy and acceptance approach for CLPS.

Estimated Completion Date: June 30, 2021.

To improve NASA's guidance, communications, and management controls of special hiring authorities to help fill or retain critical knowledge and disciplines, the OIG also recommended the OCHCO, in coordination with Center management and technical capability leaders do the following:

Recommendation 11: Develop procedures for periodic communication of the available hiring authorities, including but not limited to NEX and Pathways, guidance regarding the use of hiring authorities and the tools resident on USAJOBS.gov, monitoring of usage, and identifying and reporting usage challenges to Center and senior management.

Management Response: NASA concurs with this recommendation. OCHCO will brief PSD and relevant NASA Center Management on currently available hiring authorities and the processes and procedures for their use highlighting where the information can be found in the HR Portal (hr.nasa.gov). OCHCO will continue its practice of just-in-time consultation to ensure that hiring managers are aware of hiring authorities during the recruitment process. OCHCO Human Resources Business Partners currently utilize hiring dashboards to monitor the usage of all hiring authorities and this will be shared on a regular basis with PSD and NASA Center management to encourage the use of all available hiring options. Additionally, we will include usage of hiring authorities across the SMD community during an annual Baseline Performance Review briefing.

Estimated Completion Date: March 31, 2021.

We have reviewed the draft report for information that should not be publicly released. As a result of this review, we have not identified any information that should not be publicly released.

Once again, thank you for the opportunity to review and comment on the subject draft report. If you have any questions or require additional information regarding this response, please contact Mr. Peter Meister on (202) 358-1557.

Thomas Zurbuchen Digitally signed by Thomas Zurbuchen Date: 2020.09.09 10:15:46 -04'00'

Thomas H. Zurbuchen, Ph.D.
Associate Administrator
Science Mission Directorate

JANE DATTA Digitally signed by JANE DATTA Date: 2020.09.08 17:32:17 -04'00'

Jane Datta
Deputy Assistant Administrator
Office of Human Capital Management

APPENDIX D: REPORT DISTRIBUTION

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    Subcommittee on Government Operations

House Committee on Science, Space, and Technology
    Subcommittee on Investigations and Oversight
    Subcommittee on Space and Aeronautics

(Assignment No. A-19-013-00)