Draft Written Statement of
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Exploration of the Solar System: From Mercury to Pluto and Beyond
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Mr. Chairman, Ranking Member Johnson and members of the Committee, thank you for the invitation to appear before you today to share my view of the exciting future of our nation's solar system exploration program. It is an honor to be seated at this table with some of our world's planetary science heroes. My name is Robert D. Braun. I'm an engineer and a technologist. The views I express today have been shaped through a 28-year aerospace engineering career in government, industry and academia. I started my career as a member of the technical staff of the NASA Langley Research Center. As a young engineer at Langley, I was given the freedom to dream big. I developed advanced space exploration concepts, led multiple technology development efforts, and contributed to the design, development, test and operation of several robotic Mars spaceflight systems beginning with the Mars Pathfinder mission, which included the first rover to visit the Red Planet.

Since 2003, I have been fortunate to serve on the faculty of the Daniel Guggenheim School of Aerospace Engineering at the Georgia Institute of Technology. At Georgia Tech, I lead a research and educational program focused on the design of advanced technologies and mission concepts for planetary exploration. Judging by the passion and creativity of the students I see everyday on the campus of Georgia Tech, this nation's grandest era of space exploration is ahead of us. It gives me great pride to work closely with these students, who are on their way to creating economic, national security and societal value for our nation through our space program.

In 2010-2011, I was honored to serve as NASA's first Chief Technologist in more than a decade, creating and leading the development of a spectrum of broadly applicable technology programs designed to build the capabilities required for our nation's future space missions. I presently serve as Vice Chair of the National Research Council's Space Studies Board and Chair of the Standing Review Board Chair for the Mars 2020 Project. However, I am here today as an individual and the views I express are mine alone.

Solar System Exploration

Planetary science is one of America's crown jewels. A unique symbol of our country's technological leadership and pioneering spirit, this endeavor has consistently demonstrated that the United States is a bold and curious nation interested in discovering and exploring the richness of worlds beyond our own for the betterment of all. In addition to informing our worldview, these missions are inspirational beacons, pulling young people into educational and career paths aligned with science, technology, engineering and mathematics, the foundation of continued U.S. economic competitiveness and global leadership in a world that is becoming more technologically advanced with each passing year.

We are not alone in this enterprise. The emergence of the Chinese and Indian space programs and the continued successes of the European and Japanese programs illustrate that, much like human exploration, robotic exploration of space is an international priority – a way to gain scientific knowledge, global prestige and advance technological capability. In the coming decade, China is preparing a series of robotic lunar missions, Russia is preparing lunar, Venus and Mars missions, India is planning to follow-up on its successful Moon and Mars experiences, Japan is planning a second asteroid sample return mission, the United Arab Emirates is planning a Mars mission, and following up on the flight of the Rosetta spacecraft and Philae lander, the Europeans are headed to Mercury, Mars, and Jupiter. Clearly, other nations believe that solar system exploration is a worthwhile endeavor and a credible measure of scientific innovation, engineering creativity, and technological skill.

Beginning with the flight of Mariner 2 more than 50 years ago, the United States has consistently led the robotic exploration of our solar system. Decade-by-decade, we have created, flown and operated a balanced portfolio of missions to explore destinations across the solar system. In just the past decade, we have proven that large quantities of water once flowed across the Mars surface, that vast hydrocarbon seas exist on the surface of Titan, and that there is a diverse set of ice-encrusted worlds in our own solar system waiting to be explored. Today, as we celebrate the success of the New Horizons mission to Pluto and the Dawn mission to Vesta and Ceres, another U.S. spacecraft is enroute to Jupiter, two U.S. rovers trundle across the Martian surface, and U.S. orbiters at Mars and Saturn are returning tantalizing insights. We have learned that our solar system and other planetary systems are exceedingly diverse. From the dusty plains of Mars to the subsurface ocean of Jupiter's moon Europa to the hydrocarbon seas on Saturn's moon Titan to the thick carbon dioxide greenhouse of Venus, there remains much to discover in our cosmic backyard.

Moving beyond the investigations carried out by our initial robotic emissaries, there is no shortage today of scientifically compelling mission concepts, designed to answer fundamental questions about who we are, where we may have come from, where we are going and—perhaps the most fundamental of them all—are we're alone? Potential planetary science missions of the next decade include returning scientifically selected samples from Mars, accessing the Mars subsurface, analyzing and returning samples from the nucleus of a comet, sampling the liquid water of one or more ocean worlds, surveying the geology of the Venus surface, sailing the hydrocarbon seas of Titan, exploring the mysterious ice giants Uranus and Neptune that stand like sentinels at the solar system's edge, and perhaps, one day, setting sail on an interstellar journey to another Earth. Clearly, there is no shortage of exciting vistas remaining for us to explore. These missions require technology development to improve or enable scientific return, reduce cost, or improve the cadence of our exploration journey. Using our past NASA technology development experiences as a guide, I will discuss these technological advances in my testimony today.

Ocean Worlds

As our exploration journey expands, a compelling scientific theme focused on the diversity and distribution of liquid resources across the solar system is beginning to emerge. On Earth, where there is liquid water, there is life. As such, investigation of our solar system's ocean worlds has potentially profound ramifications for understanding the emergence of life on Earth as well as the potential for life elsewhere in our solar system and across the universe. In addition to Earth, our present list of ocean worlds includes Jupiter's moons Europa, Ganymede and Callisto, Saturn's moons Enceladus and Titan, and Neptune's moon Triton. Enceladus and Europa may be the two worlds in our solar system best suited to search for life as we know it; Titan is likely the best place to search for life as we don't know it.

In my view, accessing water, in destinations where we know it exists, is the next great planetary science quest; one that may provide the answers to our fundamental questions regarding the potential for life across our solar system and the universe. To address these questions, we need to return to the outer planets with regularity and consistency of purpose. We need to work together to ensure future missions access the water at destinations in which we know it to exist. It is worth noting that today, even considering the work being done towards a mission to Europa, there are no planned missions in NASA's planetary science portfolio that would accomplish this.

Now is the time to organize and initiate a series of robotic missions focused on the fundamental questions of evolution, habitability and life across our solar system's ocean worlds. It is worth remembering that prior to flight of the Mars Pathfinder and Mars Global Surveyor missions in 1997, our nation went 20 years without the Mars Exploration Program that is today a central part of our U.S. space exploration identity. Spurred by the technology advances of these two missions (e.g., direct entry and aerobraking, among others), NASA changed the game at Mars, successfully implementing these missions for approximately one quarter the price of past mission concepts and unsuccessful attempts. These technologies and approaches fueled the creation of the Mars Exploration Program and its associated budget line, allowing for an increase in mission cadence that has enabled our advancement of Mars scientific knowledge over the past two decades.

In a similar vein, direct access to our solar system's oceans is now both technically and fiscally viable. Recall that it has not been any one mission or science measurement that has singularly changed our view of Mars. Rather, it has been the synthesis of evidence, gathered through an integrated set of measurements, obtained by a carefully engineered sequence of missions. Advancing Mars science required a prioritization of investigations, opportunities for relatively frequent launch, and a building-block approach in which technology advancement was made across a series of interconnected missions to improve science return over time. Built upon these same principles and the scientific foundation obtained from past missions, exploration of our solar system's ocean worlds is possible today as a result of critical technology investments and new capabilities that may bring the outer planets within reach of a broad set of missions.

At present, NASA is formally initiating the Europa Mission in accordance with the objectives of the planetary science decadal survey. However, going all the way to Europa without touching its surface is like driving across the country to Disneyland and then staying in the parking lot.

Viewed through a program lens, the addition of a small, astrobiology-focused lander to directly access the surface of this ocean world should be considered for potential launch with the Europa Clipper. A science-focused technology demonstration that proves our ability to safely and precisely access the fundamentally different surface environment of these ocean worlds should be the primary objective of this first U.S. outer planets lander. Providing unique imagery and chemical analysis of the icy moon terrain, such a mission would be a pathfinder for a suite of future surface and subsurface astrobiology missions to access the water in these ocean worlds. Compiled as a sequence of interconnected missions, this is a journey sure to inspire the world and maintain U.S. leadership in space exploration.

Technology Enables Our Exploration of the Solar System

Numerous engineering and technical challenges need to be addressed to advance U.S. scientific exploration of the solar system. Because the transit times, distances, radiation environment and surface environments of these worlds differ so significantly from vistas we have previously visited and understand, new engineering capabilities and technical expertise must be developed, particularly to land, rove or dive at one of these destinations. If planned and managed appropriately, broadly applicable technology investments can be utilized to bring the exploration of these worlds within our reach.

Technology advancements being pursued today can greatly reduce the cost and increase the capabilities of future spaceflight systems for the exploration of a broad range of destinations, including the outer planets, their ocean worlds, Venus and Mars. Fortunately, many of the needed technologies, including advanced power systems (both solar and nuclear), radiation protection, sensing, landing, navigation and communications were identified for funding in the FY15 House Appropriations bill. These technology development activities have the potential to bring a broad range of compelling new missions into the realm of possibility, including Discovery, New Frontiers and Flagship class missions to outer planet destinations. Coupled, with the fielding of a heavy lift launch capability, presently in development by NASA and U.S. industry, an increased cadence and widening aperture of outer planet missions is possible in the decade of the 2020s.

NASA has a successful track record in the development of game-changing technologies and mission implementation approaches to enable planetary science. Consider the following short list of illustrative examples that span propulsion, power and atmospheric entry technologies:

Solar Electric Propulsion (SEP): In 1994, NASA initiated the New Millennium Program to develop and demonstrate technologies for future space science and exploration missions. The New Millennium Program flew its first deep space mission, Deep Space 1 or DS-1, in 1998. DS-1 included flight qualification of a dozen new space technologies, most of which have subsequently found their way into current NASA missions. However, the true superstar technology on DS-1 was the NSTAR solar electric powered ion propulsion system. DS-1 not only successfully demonstrated this revolutionary SEP system, but showed through its primary and extended missions the ability of SEP missions to encounter multiple comets (Braille and Borrelly), a technical feat not possible with traditional chemical propulsion systems. As a direct result of the flexibility of the SEP system (and unlike any previous planetary science mission), the DS-1 mission plan allowed for the selection of which comets to visit and for what timeframes during the performance of the actual mission.

With the DS-1 mission completed, this technology was ready for mission infusion. The demonstrated SEP efficiency, reliability and mission flexibility carried over directly into the competitively selected Dawn mission. Launched in 2007, Dawn is powered by a DS-1 class SEP system operating at 10 kW, and like DS-1, has for various reasons needed to adjust it mission trajectory on the fly. Today, after nearly eight years of operations, and with the first scientific data set of Ceres continuing to be returned to scientists and the public here on Earth, it is clear that SEP technology has revolutionized the art of the possible in terms of space science and exploration. These advances in solar electric propulsion technology are useful beyond the scientific domain. Ion thruster technology has been transferred from these missions to the commercial satellite industry, and today most of our new geostationary communications satellites use ion thrusters to meet their orbital propulsion needs.

Solar Power: Following decades of investment in solar-cell technology by both government and industry, NASA conceived, designed and is now operating the first solar-powered robotic mission to Jupiter (Juno). In this case, solar power is used to operate the spacecraft as opposed to power its propulsion system. This distant location from the Sun is a regime where only nuclear-powered spacecraft were once thought possible. This breakthrough is enabling collection of planetary science through a New Frontiers mission at a cost not possible through alternative means. This same high-efficiency solar cell technology is now making its way into other space science missions, including the Europa Mission as well as the solar power infrastructure that supports our society here on Earth.

In the past few years, the Space Technology Mission Directorate has demonstrated innovative solar array structures whose mass has been cut in half and packaging volume reduced by two thirds. To further promote science mission infusion potential, NASA has offered this technology as Government Furnished Equipment in the most recent SMD Discovery solicitation. Coupling the efficiency improvements of the solar cells themselves with these gossamer solar array structure improvements, NASA investments in this technology appears poised to benefit the U.S. commercial telecommunications industry. SSL, Lockheed Martin, Boeing and ATK have held discussions with NASA regarding future utilization of these solar power systems, improving the performance and affordability, while reducing the mass, of future communications satellites.

PICA Heatshield: Following a decade of investment in lightweight carbon ablators, NASA matured the high-performance thermal protection system PICA that has enabled analysis of dust samples obtained from a comet following safe completion of the highest speed Earth reentry of all time (Stardust). Demonstrating the broad applicability of this technology, PICA was utilized to enable entry of the Mars Science Laboratory (MSL) after a potentially catastrophic problem was uncovered late in the development cycle of the initially-planned thermal protection system material. NASA's technology development efforts provided the mature PICA solution at precisely the needed instant in time, allowing the mission to move forward successfully. Without the prior development and availability of PICA, the Curiosity landing may never have occurred. Since that time, the SpaceX Dragon capsule has adopted a form of PICA as its heatshield material, while the Orion project also considered this material for potential use.

These examples of technology infusion share a common characteristic - each was matured from broadly applicable space technology roots, not mission-focused objectives. For example, when the time came for flight project development, Stardust and Mars Science Laboratory did not need to be planned inclusive of the cost and risk associated with the maturation of the PICA heatshield material. Rather, technology development efforts external to these flight programs had already retired these risks and handled these costs. Similarly, Juno did not need to be planned inclusive of the cost and risk associated with the maturation of high-efficiency solar cells. DS-1 was not planned as a technology precursor to Dawn; however, its success certainly enabled Dawn's competitive selection as a Discovery mission. Removing this technology development risk has been cited numerous times by the GAO as a means to better manage NASA's future spaceflight missions. This is the principle upon which NASA's Space Technology Mission Directorate was built. Such an approach is also one of the cornerstones of the N.A.C.A. and the 1958 Space Act that authorized NASA.

Technology Investments Bring the Outer Planets Within Our Reach

A broad range of technology advancements and alternate mission implementation approaches are needed to allow for the conduct of compelling deep-space missions at various scales including NASA's New Frontiers and Discovery-class missions. For example, low mass avionics and power systems capable of operating reliably at very low temperatures will enhance or enable a broad set of deep space missions. Listed below are six technology areas that are critical to explore our solar system's ocean worlds or complete other compelling science missions outlined in the NRC Planetary Science Decadal Survey.

Radioisotope Power Systems (RPS): Space exploration missions require safe, reliable, long-lived power to provide electricity and thermal energy to the spacecraft and their science instruments. One source of power, particularly for missions far from the Sun, is the Radioisotope Thermoelectric Generator (RTG) that reliably converts heat into electricity through the natural decay of plutonium. RTGs have been safely used on solar system exploration missions since the 1970s, including Pioneer, Voyager, Ulysses, Viking, Galileo, Cassini, Curiosity, and New Horizons. Such systems were also used in the Apollo program. Today, Multi-Mission Radioisotope Thermoelectric Generators (MMRTGs) are the only viable RPS option for planetary exploration missions. With a mass of 45 kg, each MMRTG is capable of generating 125 W of power at the beginning of its life. For approximately five years, NASA and the DOE pursued development of the Advanced Stirling Radioisotope Generator (ASRG). With a mass of approximately 20 kg, this system was designed to produce 140 W of power at the beginning of its life while using only one quarter the plutonium of a MMRTG, implying the potential availability of four times the number of systems with current materials. The ASRG achieves it efficiency through precise and rapid movement of a piston; reliably and accurately controlling this movement for the duration of a deep space mission (potentially a decade or more) is the critical breakthrough required for ASRG feasibility. In 2013, NASA greatly scaled back its ASRG activity and used these funds to maintain the DOE production line.

Given the presently planned cadence of deep space missions in need of a radioisotope power system (about one per decade), the reliability issues surrounding the ASRG, and the cost involved, NASA's decision in 2013 was certainly understandable. However, in making this decision, NASA has boxed itself into a future in which expanding the pace of outer planet exploration may not be possible. Compounding this situation, NASA is currently expending little effort on MMRTG alternatives, including the previous system used by Cassini, Galileo and New Horizons which provided about double the performance (W/kg) of the MMRTG. As such, should our nation decide to increase the pace of outer planet exploration, there may be few, if any, technologies ready for NASA to apply to this challenge. A long-lived Europa lander will certainly not be solar powered; neither will a Europa submarine, or missions to explore Uranus or Neptune, sail the seas of Titan, or follow-up to New Frontiers' discoveries at Pluto. Furthermore, NASA's 2013 decision certainly penalizes potential Discovery class missions more significantly than potential Flagship missions (that can likely afford the mass impact associated with the MMRTG) at a time when we should be doing all we can to enable a diverse suite of low cost exploration missions to flourish. In my view, this is a technology problem whose solution must be addressed as part of plans to expand the exploration of the ocean abodes of our solar system. This investment in a high reliability, high performance RPS must precede the mission development funding. Without this investment, numerous deep space missions are likely to remain unattainable.

Deep Space Atomic Clock (DSAC): Precise timekeeping is essential to navigation. As the Earth and the planets move about the Sun at different rates, an accurate estimation of time is a critical part of obtaining precise position and velocity estimates. Ground-based atomic clocks have long been a cornerstone of deep space vehicle navigation, providing the baseline data necessary for precise positioning through two-way communication. The Space Technology funded DSAC project is developing a smaller and lighter version of the refrigerator-sized atomic clocks used as part of this process today at NASA's Deep Space Network (DSN) tracking stations. Use of an accurate onboard clock eliminates the navigation need to send signals from Earth to a spacecraft and back, optimizing use of the DSN to enable more efficient data return while simultaneously improving navigation performance. DSAC has direct application to gravity science and atmospheric sounding missions and is about an order of magnitude more accurate and stable than the GPS clocks in use today at the Earth, while also being smaller and lighter. Upon completion of a 2016 low Earth orbit demonstration mission, this technology will be ready for infusion on deep space missions in the early 2020s. SMD listed this technology as Government Furnished Equipment in its most recent SMD Discovery call and the DSAC is expected to be included in the same manner in the upcoming SMD New Frontiers solicitation.

Deep Space Optical Communications (DSOC): Because the power required for radio frequency communications increases with the square of the distance, the efficient and reliable return of science data to Earth is a challenge for deep space missions. For missions to Jupiter and beyond, the demands of returning science data to Earth may dominate the power budget of a spacecraft. As we look to accomplish more scientifically ambitious missions to Mars or consider the scientific exploration of Europa and other ocean worlds, a shift to a different communications architecture may be necessary. Through a partnership between SMD and STMD, NASA is incentivizing the flight of a DSOC system aboard the next Discovery mission. The system will provide a factor of ten increase in bandwidth for the same power (and at far lower mass) compared to a state-of-the-art radio frequency communications system. The system under development for this Discovery opportunity will be directly applicable to a Europa mission, providing a factor of 10 increase in bandwidth relative to traditional approaches. More importantly, the DSOC system represents the beginning of a transformation to optical communications that is occurring not only for deep space missions, but also potentially to NASA's Tracking and Data Relay Satellites (TDRS) as well as for commercial communications satellites. Within NASA, STMD is the stakeholder investor across this optical technology spectrum. Through a partnership with NASA's SCaN Office, other government agencies, and satellite manufactures, STMD will build and demonstrate the Laser Communications and Relay Demonstration (LCRD) in geosynchronous orbit.

Terrain Relative Navigation (TRN): Most planetary landing systems utilize onboard inertial navigation to compute position and velocity based on accelerometer and gyroscope measurements. In TRN, a vehicle's position is estimated by autonomously comparing local terrain measurements (e.g. imagery) with an onboard map. In this manner, the vehicle effectively navigates using the local terrain and can land with great precision relative to local terrain features of scientific interest. For example, recent Mars landing studies have estimated that with TRN, the approximate +/- 10 km Mars Science Laboratory landing footprint could have been reduced to +/- 100 m. This technology may also be fused with science sensors or other sensor measurements to create and intelligent landing system capable of setting down close to scientifically interesting locations, dramatically reducing, and, in the extreme, possibly eliminating the need for significant surface mobility. This technology would significantly improve science return at locales, such as Europa and Titan, where only cursory landing site information may be available. Such a system may enable feasible surface science missions with greatly reduced mobility requirements (and associated cost). In addition to the outer planets, TRN is applicable to Mars landings (this technology is presently under consideration for flight on the Mars 2020 mission) and was baselined in prior plans for human exploration of the Moon.

Ocean Worlds Landing Testbed: Because landing on an ocean world requires overcoming dramatically different challenges than those destinations at which the U.S. has landed previously, development of an ocean worlds landing testbed (analogous to the JPL Mars yard used for rover testing) is needed to allow advancement of the broad range of landing architectures, technologies and capabilities required for safe access to the new and diverse surface and subsurface environments found at these vistas. This testbed would also enable development and testing of ocean worlds surface and subsurface mobility systems (e.g., melt probes).

Heatshield for Extreme Entry Environment Technology (HEEET): Today, many of the same technologists at the NASA Ames Research Center that developed PICA are maturing a woven thermal protection system material capable of withstanding the harsh aerothermodynamic environment associated with flight through the atmospheres of Saturn, Uranus or Venus. This technology development is enabling to several potential missions described in the NRC Planetary Science Decadal Survey. Without HEEET, these missions are significantly constrained by the use of heritage carbon phenolic materials that have not been manufactured in more than a decade. Funded by the Space Technology Mission Directorate, this technology was offered as Government Furnished Equipment in the recent SMD Discovery call and is anticipated to be included in the same manner in the upcoming SMD New Frontiers solicitation. Without this technological solution, it is likely that missions to the surface of Venus, or to study the atmospheres of Saturn or Uranus would not be feasible. The partnership between STMD and SMD to develop and potentially infuse HEEET is representative of how NASA can effectively manage technology development for future missions, allowing potential NASA science missions that otherwise would simply not be possible.

Within NASA today, much of the longer-term technology development work is performed within the Space Technology Mission Directorate, with nearer-term, science mission technology investments largely managed within the Science Mission Directorate. Clearly, this approach requires STMD and SMD to work together for the advancement of planetary science. There is ample evidence to suggest that this relationship is flourishing. For example, the latest Discovery call included the NASA provision of five STMD developed technologies: DSAC, DSOC, HEEET, Advanced Solar Arrays, and a Green Propellant technology alternative to hydrazine. STMD and SMD are also co-funding and number of advanced development efforts. Equally important, without the technology investments contained within the Space Technology budget line, missions to access the Mars subsurface, analyze and return samples from nucleus of a comet, sample the liquid water of one or more ocean worlds, survey the geology of the Venus surface, sail the hydrocarbon seas of Titan, or return to Pluto will likely remain just out of reach of lower cost and potentially higher cadence mission opportunities.

Summary

Planetary exploration is a unique symbol of our country's technological leadership and pioneering spirit. We are fortunate to be part of a society that can fulfill the responsibility of expanding humanity's reach from the cradle of Earth throughout the solar system. Working at the intersection of science, engineering and technology, our solar system exploration missions yield a return far greater than the funding invested. The challenges of these missions inspire our children, build the scientific and engineering literacy of our country, and increase our economic and technological competitiveness. We have now completed a first investigation of each major body in our solar system. There is still so much to learn. Fueled by new technological capabilities and mission implementation approaches, compelling scientific discoveries are within our grasp. However, without appropriate technology investment, these dreams will not be realized.

Now is the time to accelerate, not curtail, the pace and scope of our nation's solar system exploration program. Our nation needs to dream big, and achieving large goals is precisely what America has come to expect of NASA's solar system exploration program. Through our exploration missions to date, a major scientific quest focused on fundamental questions of evolution, habitability and life across our solar system's ocean worlds has begun to emerge. Coupling our scientific drive with investment in the critical technologies required to accomplish these future missions at a risk posture commensurate with robotic exploration is the only way to achieve the grand objectives of these future missions within reasonable cost and time scales.

Investments in NASA technology produce benefits far beyond the Agency's missions, influencing the commercial sector and society as a whole. Positive outcomes that are likely from an investment in the technologies required for our planetary science program include economic, national security, global leadership and societal benefits. As illustrated by some of the examples I have discussed today, these advances will serve to enable solar system exploration missions that would not otherwise be possible, spark a technology-based economy, and highlight internationally our country's scientific innovation, engineering creativity and technological skill.