National Aeronautics and Space Administration

NASA Strategic Space Technology Investment Plan

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NASA Strategic Space Technology Investment Plan

"Future leadership in space requires a foundation of sustained technology advances that can enable the development of more capable, reliable, and lower-cost spacecraft and launch vehicles." – *America's Future in Space: Aligning the Civil Space Program with National Needs,* National Research Council

National Aeronautics and Space Administration

Office of the Administrator
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Investment in space technologies is key to leadership in space and in supporting the economy; however, NASA for years did not have a strong focus on technology. In 2010, the President and Congress unveiled an ambitious new direction for NASA which included renewing investment in space technology. This new path forward calls for NASA to maintain an Agency space technology enterprise that aligns mission directorate investments, increases capability, lowers mission cost, and supports long-term needs. It also directs aggressive and prioritized technology investments that will support NASA's exploration and science missions and will also support other Government and commercial space activities.

This ambitious new direction requires a sustainable plan that integrates NASA's technology activities while contributing to the Nation's innovation economy. The following Strategic Space Technology Investment Plan provides the guidance for NASA's space technology investment during the next four years, within the context of a 20-year horizon.

This plan will help ensure that NASA develops technologies that enable its objectives: to sustain and extend human activities in space, explore the structure, origin, and evolution of the solar system, and search for life past and present. The plan will help us expand our understanding of the Earth and the universe and will have a direct and measurable impact on how we work and live. It also identifies pioneering and crosscutting technologies that will energize domestic space enterprise and extend benefits of space for the Nation.

NASA's Strategic Space Technology Investment Plan was created after the Agency developed a series of draft Space Technology Roadmaps. Following careful review of the draft roadmaps by the National Research Council, with input from the public and key stakeholders, NASA finalized this new investment plan.

NASA's legacy continues today through a balanced portfolio of technology development at all stages of technological maturity. Using this plan, NASA will continue to invest in revolutionary concepts that help develop the Nation's workforce and innovation community. We will generate transformative and crosscutting technology breakthroughs that enable our missions and benefit the commercial sector. And we will collaborate with others to create new ideas and markets that strengthen our economy and contribute to U.S. technological global leadership.

Technology enables the journey of discovery and advancement. We look forward to working with the Nation to grow our technological base and take the journey to expand scientific understanding, explore the universe, and make a positive impact on the lives of all of those around us.

Charles F. Bolden, Jr.
Administrator

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Overview

"Sparking the imagination and creativity of our people, unleashing new discoveries—that's what America does better than any other country on Earth. That's what we do....We need you to seek breakthroughs and new technologies that we can't even imagine yet." - From President Obama's speech on innovation at Penn State University, 12:35 PM, February 3, 2011.

For more than 50 years, the National Aeronautics and Space Administration (NASA) has been at the forefront of scientific and technological innovation in the United States. NASA's investments in space technology have helped make the United States the global leader in space. To guide this legacy of innovation into the future, NASA has established the NASA Strategic Space Technology Investment Plan (NASA SSTIP).

The NASA SSTIP is a comprehensive strategic plan that prioritizes space technologies essential to the pursuit of NASA's mission and achievement of national goals. The NASA SSTIP provides a focused investment approach to guide NASA's space technology investment over the next four years within the context of a 20-year horizon. The framework guiding this investment approach is a four-pillar system of goals to ensure NASA investments optimize the benefits of key stakeholders, including NASA Mission Directorates, other U.S. Government agencies, the private sector, and the national economy. The NASA SSTIP specifies principles of execution for this plan as well as a governance strategy that allows for updating the plan on a biennial basis. This plan does not offer guidance or direction for aeronautics technology development, which is provided in other national policy documents.

NASA's efforts in space technology development represent an indispensable contribution to a revitalized research, technology, and innovation agenda for the nation. These investments stimulate the economy and enhance America's global economic competitiveness through the creation of new products and services, new business and industries, and high-quality, sustainable jobs. This investment strategy maximizes the benefit of taxpayer dollars to NASA, other Government agencies, private sector space activities, and ultimately, the nation.

Background

Space Technology: Stepping Stones to the Future

Since its establishment, NASA has helped spur profound changes in our nation's scientific knowledge, culture, and expectations. NASA's innovative technology development programs have enabled important space science and exploration missions, contributed to other U.S. Government agencies' needs, cultivated commercial aerospace enterprises, and helped foster a technology-based U.S. economy. *Rising Above the Gathering Storm, Revisited*, a report by the National Research Council (NRC), addresses the link between technology development efforts and the economy, noting that various studies indicate a strong link between economic growth and technological innovation in recent decades.[1]

Looking forward, NASA must continue to blaze the trail for space science and exploration—and enhance national innovation and economic growth—through the development of technologies that provide capabilities fundamental to the Agency's direction and the U.S. space enterprise. For example, as NASA undertakes increasingly challenging human missions to deep space destinations, it is essential the Agency identify and mature technologies that can increase the affordability, safety, and feasibility of such missions and ultimately, enable travel to and exploration of destinations never before visited.

In 2010, the Administration updated the U.S. National Space Policy, which recognizes the essential role of space for our national and global economic well-being and provides direction on U.S. Government roles and responsibilities concerning space activities, including NASA's role in advancing space science, exploration, and discovery. For space-related research and development, the U.S. National Space Policy incorporates guidance on topics such as enhancing interagency coordination of technology development activities and increasing the emphasis on certain technology arenas. It also directs NASA to work with industry, academia, and international partners in implementing a new space technology development and test program to build, test, and fly key technologies that can increase capabilities, decrease costs, and improve sustainability, safety, and affordability while expanding opportunities for future space activities. Finally, the policy encourages the growth of a U.S. commercial space sector that supports U.S. needs, is globally competitive, and advances U.S. leadership in new market generation and innovation-driven entrepreneurship.

Also in 2010, the President and Congress unveiled an ambitious new direction for NASA that includes renewed investment in space technology development. This new approach calls for NASA to grow and maintain an Agency space technology base that helps align Mission Directorate investments, increase capabilities, lower mission cost, and support long-term needs. It also directs aggressive and prioritized technology investments that support NASA's robotic and human exploration missions as well as other government agencies and the commercial sector.

Technology Development as a Priority

In 2010, the NASA Administrator re-established the role of an Agency-level Chief Technologist to provide NASA a principal advisor on matters concerning Agency-wide technology policy and programs. This establishment was aligned with a Government-wide emphasis on advancing technology to spur innovation and brought a renewed focus within NASA to rapidly mature technologies for space exploration.

> **Technology Definition:** A solution that arises from applying the disciplines of engineering science to synthesize a device, process, or subsystem, to enable a specific capability.

In collaboration with the Office of the Chief Technologist (OCT), the Space Technology Program (STP) develops pioneering and crosscutting technologies that enable multiple missions for internal and external stakeholders. These technology development activities span the range of technology readiness from levels 1 through 7, always with an eye toward infusion into the Mission Directorate programs. The NASA Mission Directorates develop and mature technologies required to advance capabilities specific to current missions or planned future missions. Such efforts are often focused on higher technology readiness levels, and they tend to emphasize the incorporation or packaging of new technologies into subsystems with particular mission applications. Mission Directorates' technology programs fund low readiness level technologies and basic research that advance readiness for future activities when such work is outside the scope of the Space Technology Program.

OCT leads and advocates for technology development at NASA and for NASA. Among other key functions, OCT works to infuse technologies into future NASA missions, facilitates Agency technology governance (such as risk acceptance and reporting), and documents, demonstrates, and communicates the societal impact of NASA technology investments. In addition, OCT seeks transformative opportunities by incorporating technology innovations from other parts of the technology economy, such as cell phones, cloud computing, and biotechnology. Finally, OCT leads technology transfer and technology commercialization activities across the Agency, facilitating broader dialogue with the private sector, and rewarding innovation across the NASA workforce.

To ensure NASA implements this development architecture, OCT established the NASA Technology Executive Council (NTEC), which brings together the Mission Directorate Associate Administrators, the NASA Chief Engineer, and the Chief Health and Medical Officer. The function of NTEC is to perform Agency-level technology integration, coordination, and strategic planning. For example, in early 2012, NTEC formally approved the expansion of the Space Weather Working Group to include space radiation within its scope and to develop a white paper that outlines specific strategies and needed technologies to mitigate space radiation problems, per the request of the NRC. Among other recent actions, NTEC reviewed the NRC's analysis of the Space Technology Roadmaps and the NRC's recommended priorities and approved the development of the inaugural NASA NASA SSTIP.

Developing a Strategy

NASA now has an Agency-wide structured plan for near- and far-term space technology development. This plan began to take shape in 2010, when NASA developed the draft Space Technology Roadmaps—14 plans for developing technologies in 14 essential space technology areas over the next 20 years. NASA then requested the NRC to review the Space Technology Roadmaps and provide recommendations for improvement. In 2012, the NRC released its final response to the Space Technology Roadmaps. In this response, the NRC listed the roadmaps' 100 top technical challenges and 83 high-priority technologies and articulated three overarching technology objectives for NASA. The NRC also chose 16 of the 83 high-priority technologies as the top priorities for achieving these technology objectives. (Appendix C provides more information about the Space Technology Roadmaps, the NRC's response, and other details on the NASA SSTIP development process.) With the Space Technology Roadmaps, the NRC's response, up-to-date information on every NASA space technology project, input from internal and external stakeholders, and guidance from NASA senior leaders, OCT developed this strategy for NASA's space technology investments.

NASA's Strategy

Investment Approach

NASA's space technology investment approach is designed to focus on technology development activities that will rapidly produce critical needed capabilities that have the potential to revolutionize the way we explore, discover, and work in space. This approach creates three levels of investment concentration to guide future space technology expenditures. These levels of concentrated investment are known as Core, Adjacent, and Complementary (as shown in Figure 1).

Core technology investments are the central focus of NASA technology investment and will comprise approximately 70 percent of the Agency's portfolio over the next four years. Core technologies represent the majority of the NRC's top priority recommendations (shown in Figure 2) and the mission-specific technologies. Core technology investments include near-term technology investments necessary to accomplish mission-specific objectives and eight pioneering and crosscutting technology investment areas. The eight Core technology investments are pressing needs that must begin development as soon as possible. They are described in detail below.

Adjacent technology investments represent additional high-priority investments and will comprise approximately 20 percent of the Agency's portfolio over the next four years. Adjacent technology investments relate to the Core investments that are not strategically indispensable. Adjacent technologies are not part of the Core technologies but are part of the NRC's 83 high priorities. Their development may take more time than the pressing needs identified in the Core.

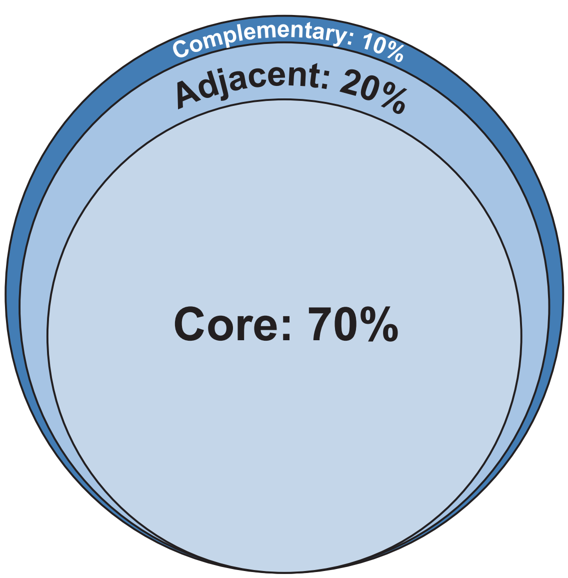


Figure 1. Three levels of focused technology investment applied to SSTIP framework.

Complementary technology investments include the remaining needed space technologies uncovered in the Space Technology Roadmaps and assessed by the NRC. They represent breadth, where Core and Adjacent technologies represent depth. Complementary technology investments will comprise approximately 10 percent of the Agency's portfolio. These investments are characterized by limited immediate relevance. They include technologies with

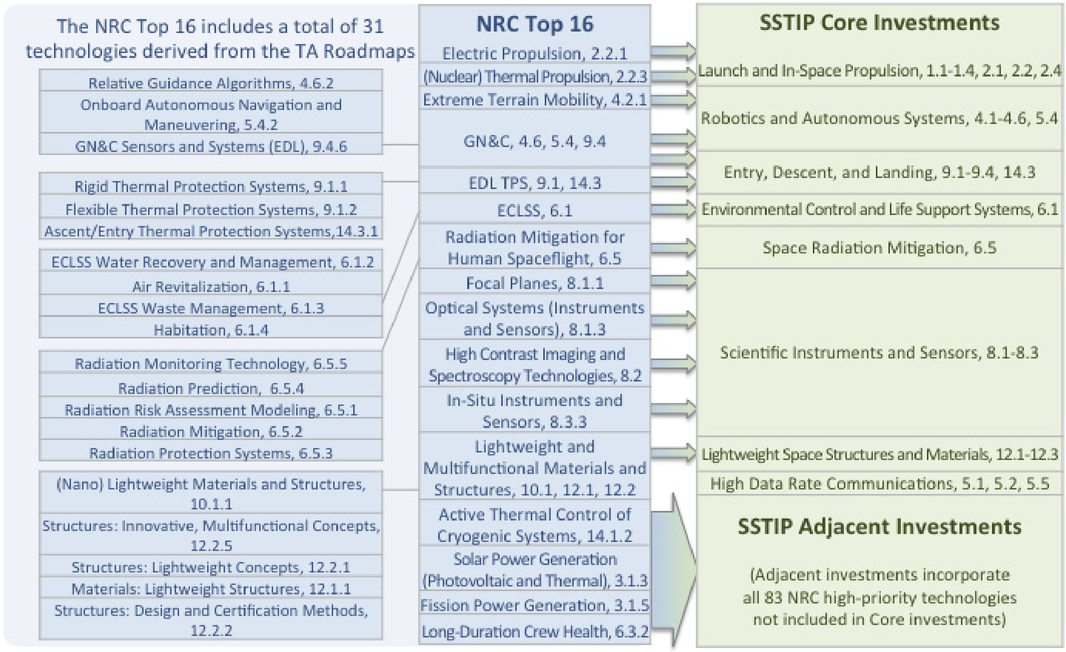


Figure 2. SSTIP Core and Adjacent investments incorporate NRC-recommended high-priority technologies.

the potential to bear relevance within the 20-year horizon of this strategic plan, although investing now ensures that those that can bear fruit sooner are given the chance to do so. This set of investments completes the strategic approach by ensuring NASA casts a wide net, seeding future innovation. In some cases, Complementary technologies depend on other technology development for completion or far-term need dates.

Throughout all three areas, NASA is maturing technologies needed for future science discovery and exploration applications and developing technologies with a range of development cycles.

Technologies at various stages of maturity may be pursued across all three levels of investment. As recommended by the NRC, at least 10 percent of NASA's overall technology portfolio will be at a low technology readiness level (TRL), including basic principles (TRL 1) and the formulation of technology concepts or applications (TRL 2). Table 1 provides brief descriptions of NASA's Technology Readiness Levels.

Technology Readiness Level (TRL) Definitions

TRL 1	Basic principles observed and reported
TRL 2	Technology concept and/or application formulated
TRL 3	Analytical and experimental critical function and/or characteristic proof of concept
TRL 4	Component and/or breadboard validation in laboratory environment
TRL 5	Component and/or breadboard validation in relevant environment
TRL 6	System/subsystem model or prototype demonstration in a relevant environment
TRL 7	System prototype demonstration in an operational environment
TRL 8	Actual system completed and "flight qualified" through test and demonstration
TRL 9	Actual system flight proven through successful mission operations

Table 1. Technology readiness level definitions.

Source: NPR 7120.8

By defining and coordinating technology investment in this way, NASA seeks to realize the greatest benefit from its investments for the Agency, its stakeholders, and the nation.

Framework

The Core, Adjacent, and Complementary technologies support the goals of NASA's internal and external stakeholders, which the NASA SSTIP summarizes in a four-pillar framework. Each of the pillars of NASA's space technology strategy includes three components: a strategic investment goal, associated capability objectives, and technical challenge areas underpinning those objectives.

The strategic investment goals are:

- Pillar 1 Goal: Extend and sustain human presence and activities in space.
- Pillar 2 Goal: Explore the structure, origin, and evolution of the solar system, and search for life past and present (in-situ measurements).
- Pillar 3 Goal: Expand understanding of the Earth and the universe (remote measurements).
- Pillar 4 Goal: Energize domestic space enterprise and extend benefits of space for the nation.

This framework closely resembles the NRC's recommended objectives (Objectives A-C) and top technical challenges. Similar to the NRC's strategy to categorize high-priority technologies by the purpose of NASA missions, the first three pillars represent needed investments that enable NASA's human exploration and scientific discovery missions. The NASA SSTIP includes a fourth pillar to ensure attention is focused on supporting long-term national needs and developing space-related capabilities that contribute to the success of commercial space industry. The fourth pillar's content is influenced by crosscutting space technology needs identified in collaboration with NASA's stakeholders, including other Government agencies and private industry.

The capability objectives within each pillar must be met to achieve the associated goal. Some capability objectives, such as *Sustain Human Health and Performance*, support more than one goal. Those that show up in more than one pillar illustrate the crosscutting nature of that specific technology area and the fact that development of technologies within it can enable multiple mission types.

Within each capability objective is a list of high-priority technical challenge areas that enable the capability objective. Many of the technology challenge areas, such as the long-duration environmental control and life support system (ECLSS) and high data rate communications, also support more than one goal.

This framework gives the NASA SSTIP the appropriate context for considering how different technologies, developed according to the NASA SSTIP's investment approach, impact future space missions.

Governance

The basic challenge of this technology development strategy is to align investments with current priorities, new mission needs, and partnership opportunities, taking full advantage of leveraged resources to provide needed capabilities. This alignment changes over time as national priorities evolve, NASA completes missions, new missions begin, and new technologies are developed and incorporated into the space infrastructure and exploration activities. The challenge is made more complex as some capabilities have no apparent foreseeable solution and emerging technology capabilities are difficult to predict. Consequently, NASA's NASA SSTIP needs frequent oversight and flexibility to make adjustments that ensure NASA produces technologies offering the greatest benefit. NTEC serves as the decision-making body for directing and balancing the investment portfolio, to provide this oversight and flexibility.

Through annual assurance processes, NASA discloses risks within and beyond the Agency to ensure that stakeholders understand NASA's choices. Because technology development does not always happen onsite, NASA also leverages capabilities around the nation and the world through contracts and partnerships with private sector, academia, and other Government organizations. Such "strategic sourcing" helps the Agency manage its risks and leverages risk-appropriate and cost-effective infrastructure whether owned or not. As appropriate, NTEC will be provided with information about NASA's space technology infrastructure and capabilities and will provide recommendations to the NASA Strategic Management Council if needed.

Principles of Investment and Execution

The following six principles guide NASA's space technology investment strategy and portfolio execution, with the objectives of optimizing investments, maintaining a balanced portfolio, using developed technologies, and providing transparency to the American public.

1) NASA will balance investments across all 14 Space Technology Areas in the Roadmaps.

The 14 Space Technology Areas focus on strategically identified areas where significant technology investments are anticipated and where substantial enhancements in NASA mission capabilities are needed. Breadth also allows NASA to participate in development of technological solutions addressing broader national needs in energy, weather and climate, Earth science, health and wellness, and national security. By investing in all Space Technology Areas, the Agency is better able to maintain a well-rounded and robust technology portfolio. Decisions about the level of investment and focus of investment in these 14 areas are outlined in the NASA SSTIP and will be refined, as needed, by NTEC.

2) NASA will balance investments across all levels of technology readiness.

At TRL 1, the lowest TRL, information already learned from basic research is taking its first step from an idea toward a particular application. At TRL 9, the highest TRL, the technology has been fully incorporated into a larger system, where it has been proven to work as designed, with suitable reliability, and is therefore considered operational. By investing in all TRLs for pioneering and crosscutting as well as mission-specific technologies, the Agency ensures a robust pipeline of new capabilities. NASA will also focus at least 10 percent of the total technology investment on low-TRL (1-2) concepts to ensure the pipeline is continually replenished.

3) **NASA will ensure developed technologies are infused into Agency missions.**

Technology programs within the Mission Directorates undertake narrowly focused and near-term development activities. Mission Directorates and Centers will be provided with information about the entire technology portfolio, enabling them to leverage their investment dollars in the Agency context and/or adapt technologies for their own use. Technology projects in the mid to high technology readiness levels are strongly encouraged to identify stakeholder communities up front, negotiate Mission Use Agreements that articulate technology needs in terms of infusion into missions, and ensure that larger technology investments produce the desired capabilities. For example, NASA's Technology Demonstration Missions (TDM) program selects development projects to prove feasibility in the environment of space and help advance innovations from concept to flight so they can be infused into future missions. Current TDM projects are expected to infuse new technologies in the areas of space communications, deep space navigation, and in-space propulsion capabilities into current and future NASA missions.

4) **NASA will develop technologies through partnerships and ensure developed technologies are infused throughout the domestic space enterprise.**

Fostering partnerships can leverage funding, capabilities, and expertise both within and outside the Agency to address technology barriers and provide capabilities. These cost-shared, joint-development partnerships can bring together new sources of information not only to address NASA's technology needs but also to benefit the nation.

NASA has established partnering and development programs to ensure technologies developed for NASA exploration and discovery missions are broadly available to other Government agencies and commercial industries. NASA is also exploring ways to enhance or improve its ability to increase the rate, volume, and quality of its technology transfer activities (shown in Figure 3), thereby increasing the economic impact and public benefit of Federal technology investments. Toward that end, NASA has drafted the following objectives:

- Fuel the technology transfer stream with an Agency-wide renewed emphasis in technology research and development and demonstration.
- Revise the Agency's policies on commercialization to ensure alignment with NASA's current focus on technology development and best practices in technology transfer.
- Build domestic partnerships for technology development, transfer, and

mutual benefit.

- Tie the technology transfer process at all stages of technology development, ensuring that formal technology transfer is considered at the earliest phases, when programs and activities are being formulated and acquisition planned.
- Increase the number of new technologies reported by NASA civil servants and contractors.
- Improve licensing processes and outcomes.
- Consider other tools and authorities for accelerating licensing of technologies.

Partnerships with international entities can also help advance NASA's technology goals. NASA has a long history of mutually beneficial international cooperation, which has significantly enhanced the technical and scientific return of the Agency's programs. International coordination is also particularly important as space agencies around the world consider how best to apply scarce resources toward common science and exploration objectives. For example, NASA's participation in the multilateral International Space Exploration Coordination Group, which developed the Global Exploration Roadmap in 2011, provides useful insight into the international community's overall interests and technology investment needs.

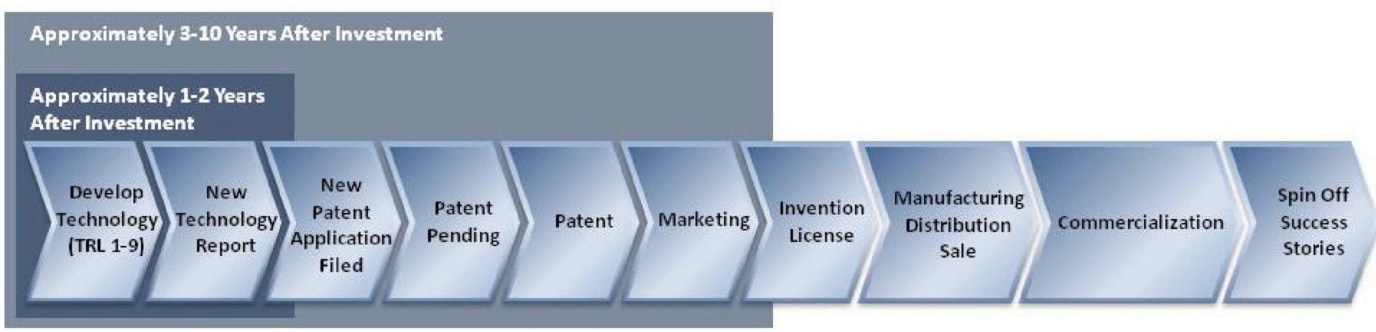


Figure 3. Summary of NASA's process for technology commercialization.

5) **NASA will use a systems engineering approach when planning technology investments.**

The Agency agrees with the NRC's recommended use of disciplined systems analysis for space technology portfolio management and decision support, and the benefits of such analysis are recognized by the Agency as critical to NASA's investment strategy. NASA's Mission Directorates currently conduct system analyses similar to that recommended by the NRC. Such analyses are vital to the establishment of the most cost-effective architectures for individual human and robotic exploration missions as well as overall suites of missions.

In the case of human exploration, for example, a "capability-driven" approach seeks to package capabilities into a logical progression of common elements needed for increasingly demanding missions. Systems analysis is conducted to identify the crosscutting technologies necessary to ensure that critical capabilities are available for the reference missions in a timely way. Common capability gates also are identified for Agency areas of interest. From this capability-driven human space exploration technology approach, the Human Exploration and Operations Mission Directorate (HEOMD) develops technology-investment strategies with incremental development steps that produce a small suite of alternatives specifically directed at achieving their desired missions. They execute these investments, monitor development progress, and make adjustments to reduce risk, thus ensuring mission accomplishment on time and within budget.

Over the next year, the Agency will carefully consider current system analysis processes and tools within NASA, as well as alternative approaches from other organizations. The Agency will identify broadly applicable methodologies that best enable NASA to effectively manage its space technology portfolio. NASA will consider current and alternative analytical approaches to not only identify technology investments but also monitor, assess, and where necessary, realign or terminate technology investments. NASA will ensure the Agency continues to efficiently develop needed capabilities, emphasizing return on investment.

6) **NASA will reach out to the public and share information about its technology investments.**

One of the NRC's recommendations on the Space Technology Roadmaps emphasized the importance of the capture, management, and sharing of space technology advancements with other Government agencies, academic institutions, commercial enterprises, and the resulting societal benefits with the general public. In response to this recommendation, OCT is undertaking an effort to develop an Agency-wide, web-based software system, NASA TechPort, to support the objective of integrating and disseminating key information about NASA investments in space technology. TechPort will offer opportunities for increased collaboration in the realm of space technology, and will enhance the visibility of NASA's Space Technology Portfolio both internally to NASA and externally to the public.

TechPort will support the capturing and tracking of innovative challenges, new technologies, and ongoing projects. TechPort capabilities will support technology infusion into NASA missions and the communication of technologies into the commercial marketplace. When the public access version of TechPort is released in the fall of 2013, it will make accessible any publicly available technology reports and provide links to patents, licenses, and software usage that emerge from NASA technology development projects.

By providing open, easy-to-use access to NASA space technology information, TechPort will facilitate technology transfer, technology partnerships, and technology commercialization activities across NASA and will extend to other Government agencies, industry, and international entities. The general public will be able to use TechPort to find technologies of interest and learn of the societal impacts of NASA's technology investments. OCT will continue to communicate the many benefits of the Agency's technology to the public through other means as well.

Core Technology Investments

The Core technologies represent focus areas of technology investment that are indispensable for NASA's present and planned future missions. Core technologies are the central focus of technology investment and will comprise approximately 70 percent of the Agency's technology investment over the next four years.

The Core technology investments have significant impact on NASA's scientific, robotic, and human exploration missions and further the technology needs of other Government agencies and the commercial sector. The Core priorities include both mission-specific technologies and pioneering and crosscutting developments.

The Core technologies are:

1. Launch and In-space Propulsion
2. High Data Rate Communications
3. Lightweight Space Structures and Materials
4. Robotics and Autonomous Systems
5. Environmental Control and Life Support Systems
6. Space Radiation Mitigation
7. Scientific Instruments and Sensors
8. Entry, Descent, and Landing

The following sections summarize the technical challenges and approach; potential impact to NASA, the nation, and NASA's partners; potential future investments; and NASA's 2012 investments in pioneering and crosscutting Core technologies. These sections were written primarily using the following sources: the Space Technology Roadmaps; the NRC report; a list of technology priorities from other Government agencies and international and commercial partners; a list of potential four-year investments compiled by the Space Technology Roadmap Technology Area teams; and an analysis of technology data from 1,237 NASA projects active in fiscal year (FY) 2012. (Appendix C provides more information about these sources.) Table 2 summarizes how each Core technology relates to the NRC's list of high-priority technologies and to the technical challenge areas across the four NASA SSTIP pillars. (Pages 44-61 provide details on the pillars and associated technical challenge areas.)

Technology Investment Classification	Technology Investments	Associated NASA SSTIP Technical Challenge Areas	Related Level 2 TABS*	Associated NRC High Priorities (Top 16 in Bold)
Core	Launch and In-Space Propulsion	Launch Propulsion Systems; High Power In-Space Propulsion; In-Space Propulsion; Cryogenic Storage and Transfer	1.1, 1.2, 1.3, 1.4, 2.1, 2.2, 2.4	**Electric Propulsion; (Nuclear) Thermal Propulsion;** Turbine Based Combined Cycle (TBCC); Rocket Based Combined Cycle (RBCC); Micro-Propulsion; Propellant Storage and Transfer
Core	Robotics and Autonomous Systems	Autonomous Systems; Robotic Maneuvering, Manipulation, Sensing and Sampling; Autonomous Rendezvous and Docking; Structural Monitoring; Robotic Maneuvering	4.1, 4.2, 4.3, 4.4, 4.5, 4.6, 5.4 (5.4.3)	**Extreme Terrain Mobility; GNC (includes Relative Guidance Algorithms, Onboard Autonomous Navigation and Maneuvering);** Docking and Capture Mechanisms/Interfaces; Small Body/Microgravity Mobility; Dexterous Manipulation; Robotic Drilling and Sample Processing; Supervisory Control; Vehicle System Management and FDIR
Core	High Data Rate Communications	High Bandwidth Communications; High Data Rates	5.1, 5.2, 5.5	Radio Systems
Core	Environmental Control and Life Support Systems	Long-Duration ECLSS	6.1	**ECLSS (includes: ECLSS Water Recovery and Management, Air Revitalization, ECLSS Waste Management, and Habitation)**
Core	Space Radiation Mitigation	Space Radiation Mitigation	6.5	**Radiation Mitigation for Human Spaceflight (includes: Radiation Monitoring Technology, Radiation Protection Systems, Radiation Risk Assessment Modeling, Radiation Prediction, and Radiation Mitigation)**
Core	Scientific Instruments and Sensors	Life Detection; Advanced Sensors (all types of detecting sensors: geological, chemical, etc.); Scientific Instruments and Sensors; Earth Observing	8.1, 8.2, 8.3	**Detectors and Focal Planes; Optical Systems (Instruments and Sensors); High Contrast Imaging and Spectroscopy Technologies; In-Situ Instruments and Sensors;** Electronics for Instruments and Sensors; Laser for Instruments and Sensors; Wireless Spacecraft Technology
Core	Entry, Descent, and Landing	Advanced Entry, Descent, and Landing; Entry, Descent, and Landing	9.1, 9.2, 9.3, 9.4, 14.3	**EDL TPS (includes Rigid TPS, Flexible TPS, and Ascent/Entry TPS); GNC (includes GNC Sensors and Systems [EDL]);** EDL Instrumentation and Health Monitoring; EDL Modeling and Simulation; EDL System Integration and Analysis; Atmospheric and Surface Characterization; Deployable Hypersonic Decelerators
Core	Lightweight Space Structures and Materials	Lightweight Space Structures and Materials; Structural Monitoring	10.1 (10.1.1), 12.1, 12.2	**Lightweight and Multifunctional Materials and Structures (includes: [Nano] Lightweight Materials and Structures; Structures: Innovative, Multifunctional Concepts; Structures: Lightweight Concepts; Materials: Lightweight Structure; and Structures: Design and Certification Methods)**

*To download the Space Technology Roadmaps and TABS sequence, visit http://www.nasa.gov/offices/oct/home/roadmaps/index.html

Table 2. Alignment of Core technologies with NASA SSTIP technical challenge areas and NRC high priorities.

Launch and In-Space Propulsion

Technical Challenges and Approach

Safe, reliable, and affordable access to low Earth orbit (LEO) is necessary for all space endeavors. Whether based on conventional liquid- or solid-based designs, launch propulsion systems have not yet exhibited the performance, design, and life margins that lead to lasting operational robustness. The high cost of access to space is a growing challenge, and it is related to the challenge of reliability and safety, as the cost of launch failure is extreme. Achieving a breakthrough in launch propulsion of sufficient magnitude to fundamentally alter the way space systems are designed and operated will likely require a number of long-term and well-funded research and development efforts. For the next four years, NASA will invest in advancing solid and liquid rocket propulsion systems, ancillary propulsion systems, and technology development of non-conventional systems to improve the cost and operation of current systems and enhance and enable future robotic and human exploration space missions.

Most in-space propulsion systems have relied on chemical energy, although electric propulsion and other non-chemical concepts have seen growing use over the last two decades. However, the relatively large mass of required chemical propellant in current chemical propulsion systems and the low efficiency achieved in expending chemical fuel limit the distance and time that a spacecraft can travel after reaching orbit, which limits the opportunities for human and robotic missions. For the next four years, NASA will invest in advancing chemical propulsion systems and developing new non-chemical propulsion technologies, such as electric propulsion, solar sails, and tethers, to enable efficient and affordable space travel and thereby expand the possibilities of robotic and human exploration. NASA is also evaluating alternatives to chemical propellants known as "green" or non-toxic propellants, because they have the potential to reduce risk on the ground.

NASA will also invest in cryogenic propellant storage and transfer technologies. Cryogenic propellants provide high-energy propulsion solutions critical to future, long-term human exploration missions beyond LEO. The challenge is developing the means of storing and transferring these propellants in space for long durations and preventing temperature fluctuations that contribute to fuel losses due to "boil off." NASA's investment in this area is consistent with NRC recommendations. The NRC identified reduced gravity cryogenic storage and handling as a near-"tipping point technology," representing a potential large advance in technology readiness from a relatively small increase in research effort. Associated NASA projects will test and validate key cryogenic capabilities and technologies required for future exploration.

Impact to NASA

Launch propulsion system development addresses technologies that enhance existing liquid and solid propulsion technologies or their related ancillary systems, or significantly advance the technology readiness levels of newer systems like air-breathing, non-conventional, and other launch technologies. Newer technologies could significantly transform the nation's space operations and mission capabilities and keep the nation's aerospace industrial base on the leading edge of launch technologies. The overall goal is to make access to space more reliable, routine, and cost-effective, by reducing launch costs 25 to 50 percent over the next 20 years, followed by a greater reduction (>50 percent) as concepts that are currently non-conventional and at a low TRL are fully developed. Improvements in these systems will help maintain the nation's leadership role in space capability.

With the exception of electric propulsion systems, all rocket engines in use today are chemical rockets; that is, they obtain the energy needed to generate thrust by combining reactive chemicals to create a hot gas that is expanded to produce thrust.[2] Advancing chemical propulsion technologies enables much more effective exploration of our solar system and permits mission designers to plan missions to fly anytime, anywhere, and complete a host of science objectives at their destinations. A wide range of chemical technologies with diverse characteristics offers the opportunity to better match propulsion systems for future missions. Developing new chemical propulsion technologies will result in technical solutions with improvements in thrust levels, specific impulse, power, specific mass, volume, system mass, system complexity, operational complexity, durability, and cost. These types of improvements promise lower transit times, increased payload mass, safer spacecraft, and greater cost efficiency.

The main advantage of non-chemical propulsion over chemical propulsion is higher specific impulse (the amount of thrust delivered per unit mass of rocket fuel). For example, the high specific impulse of electric propulsion is typically an order of magnitude greater than that of chemical propulsion systems. Electric propulsion systems are the most efficient in-space propulsion technology available for the foreseeable future. Current efforts in developing solar electric propulsion aim for an integrated propulsion system at 300 kilowatts (kW) to enhance human exploration missions. Alternatively, the reduction in launch mass enabled by nuclear thermal propulsion technologies could significantly reduce the cost and mission complexity of crewed missions to Mars. Development of these technologies will result in technical solutions that bring improvements in specific impulse, power, specific mass, volume, system mass, system complexity, operational complexity, durability, and cost efficiency.

Development of cryogenic propellants will support future, long-duration space exploration. Cryogenic propellants can dramatically increase specific impulse, thereby providing much higher performance than conventional propellants and permitting longer range missions and spacecraft capable of carrying more payload mass. Storing

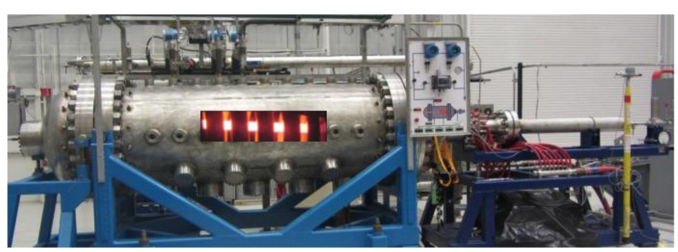


Figure 4. A key goal of the Nuclear Cryogenic Propulsion Stage project is to address critical, long-term nuclear thermal propulsion technology challenges and uses through development, analysis, and testing.

Source: NASA

cryogenic propellants such as liquid hydrogen and liquid oxygen in space for long periods of time with minimal boil-off is also critical for deep space human exploration.

Impact to Nation and Partners

NASA's commercial and international partners have cited potential benefits from investment in chemical and non-chemical in-space propulsion. For chemical propulsion, commercial partners expressed greatest interest in micropropulsion and cryogenic propulsion technologies. For non-chemical propulsion, both commercial and international partners asserted that electric propulsion technologies were high priorities of investment.

Several technologies in the area of launch, in-space, and hypersonic propulsion systems have been identified by other Government agencies as important for national mission requirements that span a broad range: from access to space, to on-orbit operations, deep space exploration, and sustained high-altitude hypersonic flight.

Potential Future Investments

Investments in chemical in-space propulsion technologies will focus on a variety of propellants, including mono-, bi-, high-energy, gel, hybrid, and solid rocket propellants.

Investments in non-chemical in-space propulsion technologies will primarily focus on solar electric, nuclear thermal, solar sail, and tether propulsion. For the next four years, potential investments in electric propulsion may include the NASA Evolutionary Xenon Thruster (NEXT) ion thruster, a Hall thruster with a desired performance parameter of 50-100 kW, and a microelectromechanical system (MEMS) electrospray with a desired power level of 100 watts. Potential thermal propulsion investments may include nuclear thermal rocket down selection and fuel development. Nuclear thermal propulsion is considered a high-priority technology for future human exploration of Mars. Two potential tether investments are high specific strength conductive tethers and a tether or payload catch mechanism.

In general, sound technology investments in launch propulsion systems will support both expendable and reusable paths of launch vehicle development. Advanced manufacturing techniques and innovative designs that are producible can lead to significant reductions in launch vehicle hardware costs. For the next four years, potential investments in solid rocket propulsion technologies include the ability to assess damage tolerance limits, detect

Figure 5. The Electrically Controlled Extinguishable Solid Propellant project is developing a thruster that would allow NASA to demonstrate an innovative throttleable solid rocket motor.

Source: NASA

damage on composite cases, develop domestic sources for critical materials used in manufacturing, and formulate advanced hybrid fuels. Investments in liquid propulsion technologies may include new liquid engine systems, propulsion materials research, high-density impulse propellants, and new subsystem modeling and design tools.

Investments over the next four years in cryogenic propellant storage and transfer can be used to enable the efficient in-space use of cryogens. In addition to propulsion, this technology can also support power reactant storage and ECLSS needs.

2012 Investments

As of this writing, NASA invests in 17 launch propulsion projects, which are all managed by programs within OCT-STP, with development in both low and medium TRLs. These projects include technologies for liquid and solid rocket propulsion systems, as well as air-breathing and ancillary propulsion systems. The Composite Cryotank Technologies and Demonstration project, managed by the Game Changing Development program, is developing advanced technologies for a low-cost, large-scale, lightweight composite cryotank for future NASA missions and commercial launch vehicles. The Manufacturing Innovation Project, also managed by the Game Changing Development program, is developing the ability to fabricate high-quality, reliable, and certifiable parts using additive manufacturing processes. The Long Duration Microgravity Tank Slosh project, managed by the Game Changing Development program, will advance the understanding of low-gravity fluid behavior to reduce mission risk and uncertainty levels.

NASA currently invests in seven chemical in-space propulsion projects, all managed by programs within OCT-STP, with development in low and medium TRLs. These projects include technologies for liquid storable, liquid cryogenic, gels, solid, hybrid, and micropropulsion propellants. The Miniaturized Low-Power Piezo Microvalve for NanoSat and CubeSat Propulsion project, managed by the Small Business Innovation Research (SBIR) program, is developing a miniature microvalve for low-rejection rate manufacturability and resilience under aggressive shock loading. The Non-Toxic Ionic Liquid Fuels for Exploration Applications project, also managed by the SBIR program, is developing and testing several new, non-toxic ionic liquid fuel formulations with low volatility for propulsion applications.

NASA currently invests in 40 non-chemical in-space propulsion projects, managed by programs within OCT-STP, the Science Mission Directorate (SMD), and HEOMD, with development in both low and medium TRLs. These projects include technologies for electric, solar or nuclear thermal, solar sail, and tether propulsion. The In-Space Propulsion Technology project, managed by the SMD Technology program, is developing technologies for electric propulsion; propellantless propulsion, such as aerocapture; sample return ascent vehicles; and Earth return systems. The project will enable access to more challenging and interesting science destinations, including enabling sample return missions. Under the Advanced Exploration Systems (AES) program, the Nuclear Cryogenic Propulsion Stage project is conducting preliminary design, fabrication, and testing of representative fuel samples and fuel elements for two primary nuclear thermal propulsion fuel forms. The In-Space Propulsion project, managed by the Game Changing Development program, is developing a 13kW-class Hall thruster with propulsion and system components, as well as a 160-220V-class power-processing unit for a Hall thruster for technology demonstration missions. The Solar Electric Propulsion project, also managed by the Game Changing Development program, is developing an ion propulsion system for the efficient use of fuel and electrical power to enable modern spacecraft to travel farther, faster, and cheaper than any other propulsion technology currently available.

NASA also currently invests in the Cryogenic Propellant Storage and Transfer (CPST) project, managed by the Technology Demonstration Mission program. This project is working to demonstrate the capability to safely and efficiently store, transfer, and measure cryogenic propellants in orbit, enabling next generation flight vehicles to store large quantities of fuel for their journeys. The CPST project will test and validate key cryogenic capabilities and technologies required for future exploration elements, opening up the architecture for large, cryogenic, in-space propulsion systems.

High Data Rate Communications

Technical Challenges and Approach

Radiofrequency (RF) communications are used on all of NASA's current space missions, but demands for more data return, at higher rates, and from greater distances require advancements on the current state-of-the-art. For the next four years, NASA will invest in advancements of traditional communication technologies, such as RF, and in developments of innovative communication approaches, such as optical communication technologies.

Impact to NASA

New developments in RF communication can allow at least two orders of magnitude increase over current data rate capabilities in deep space. Cognitive radios will be developed to sense their environment, autonomously determine when there is a problem, attempt to fix it, and learn as they operate. Communication through harsh environments such as rocket plumes and re-entry ionization will be addressed with new technologies such as ultra wide band radios. Other advancements will increase efficient use of power, available spectrum, mass, and volume.

Optical communications provide access to an uncrowded spectrum and can support the data rates needed by the next generation of science instruments. For example, the Mars Reconnaissance Orbiter's maximum data rate of six megabits per second (Mbps) (the highest of any Mars mission to date), takes nearly seven and half hours to empty its onboard recorder and one and a half hours to transfer a single high-resolution image to Earth, but an innovative optical communications solution could transmit 100 Mbps of data, emptying the recorder in 26 minutes and transferring the image to Earth in less than five minutes. An optical communications system could also dramatically improve the spacecraft positioning and thus quality of science data. Optical communications are especially valuable for deep space missions, providing higher data rates than current systems and with significantly less aperture size than current antennas.

Impact to Nation and Partners

NASA's international and commercial partners and other Government agencies have reported they could benefit from investment in high data rate communications. Other Government agencies specifically expressed interest in optical communications broadband data flow, undetectable transmissions, and wireless technologies. Commercial partners claimed they could benefit from new developments in smaller beams, increased spectrums, internetworking communications, timekeeping, and increased sensitivity.

Potential Future Investments

Potential investments to consider for the next four years include space aperture arraying for RF communications and near-Earth and deep space optical terminals.

2012 Investments

Currently, as part of the Lunar Atmosphere and Dust Environment Explorer (LADEE) mission, the Lunar Laser Communication Demonstration is scheduled to demonstrate optical communications from Lunar distance at high data rates in 2013. Another current investment in high data rate communications is the Deep Space Optical Communication project. This project develops key technologies for an operational optical deep space communications capability for future NASA scientific, robotic, and human exploration missions, providing increased sensitivity, lower mass and power requirements, and improved downlink data rate. The Laser Communications Relay Demonstration is an optical communications project that uses lasers to encode and transmit data at rates 10 to 100 times faster than radio, to deliver video and high-resolution measurements from spacecraft across the solar system.

Lightweight Space Structures and Materials

Technical Challenges and Approach

The materials used in spacecraft, propulsion systems, habitation systems, science instruments, and all other areas of a mission architecture can either enable new opportunities or limit a mission's potential. Just as a material's heavy mass, large volume, and vulnerabilities to the space and destination environment can limit a mission's capabilities, so can lightweight, compact, durable, and radiation-hard materials enable missions to spend more time in space, travel farther, and explore new destinations, like the hot surface of Venus or the high-radiation environment of Jupiter. For the next four years, NASA will invest in lightweight space structures

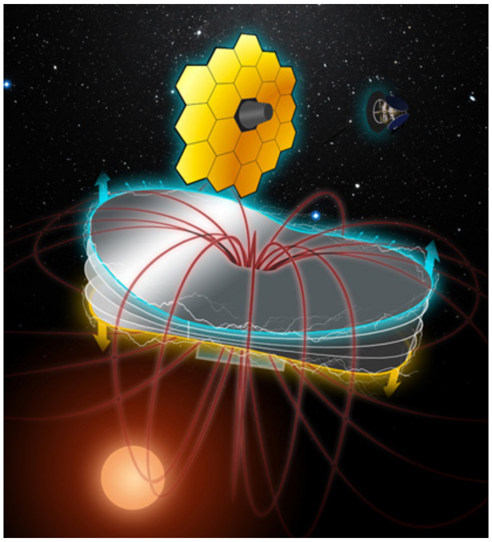


Figure 6. The High-Temperature Superconductors as Electromagnetic Deployment and Support Structures in Spacecraft project is investigating how the use of high-temperature superconductors can reduce the weight of spacecraft structures.

Source: NIAC, Miller

and materials to enable more affordable, reliable, and efficient human and robotic missions.

Impact to NASA

Advanced materials seek to overcome a wide range of challenges, such as launch mass, radiation, and micrometeoroids and orbital debris (MMOD) damage. Lightweight materials and composite structures can reduce the weight of launch vehicles, payloads, surface systems, and space structures such as cryotanks. Lightweight materials might also be used for solar sails, which use solar-photon pressure to provide fuel-less propulsion. Lightweight optical materials can be used for habitat windows and optical devices for telescopes to make them lighter and damage-tolerant. Multifunctional materials combine such characteristics as radiation protection and self-healing properties to provide space structures, such as habitats, with new capabilities and strengths. Carbon composites can enable damage-tolerant inflatable habitats, reducing launch mass and increasing volume for crew. Integrating advanced nanocomposites and nanofibers into lightweight spacecraft could reduce component weight by one-third.[3] These and more innovations in materials can impact NASA missions in multiple ways.

Impact to Nation and Partners

NASA's commercial and international partners have asserted advanced materials were a high priority for investment. One commercial partner specifically cited time-to-market improvements as a potential spinoff benefit from this technology investment.

Potential Future Investments

Investments in materials will focus on several enabling characteristics, such as lightweight, flexible, multifunctional, and electromechanical technologies. Materials development that could benefit from four years of investment includes lightweight concepts, such as hybrid laminates and non-autoclave composites. Other potential investments in materials include special materials, such as optical and self-repairing materials, and flexible materials, such as materials for an expandable habitat. In all cases, investments that ensure the materials can operate in extreme environments are required.

2012 Investments

The Materials International Space Station Experiment (MISSE) project, managed by the Technology Demonstration Missions program, has tested roughly 4,000 material samples and specimens in the space environment since 2001. These experiments are fixed to the exterior of the International Space Station (ISS) for periods of up to four years, enduring extreme levels of solar and charged-particle radiation, atomic oxygen, hard vacuum, and temperature extremes, providing insights to researchers on how to develop durable materials for spaceflight. MISSE-X will include new enhancements over the original MISSE project, including near-realtime experiment environmental exposure monitoring, daily photographing, and expanded accommodations to house more experiments and experiments with more complexity. The Lightweight Materials and Structures project, managed by the Game Changing Development program, is currently maturing technologies for large flexible substrate solar array structures to support crewed near-Earth object (NEO) missions with solar electric propulsion. This project is also demonstrating long-term durability of inflatable habitat structures for a 10- to 20-year mission life. The Composite Cryotank project is developing large, lightweight composite propellant tanks for launch vehicles and in-space stages.

Robotics and Autonomous Systems

Technical Challenges and Approach

Autonomous systems are critical for the parts of a mission that must safely and reliably operate without direct control by a human crew or ground control. As crewed and uncrewed missions travel farther from Earth, for longer periods of time, using more complex technologies and systems, space missions will require more independence, or autonomy, from ground control, and even from the crew, to operate efficiently, safely, and reliably. For the next four years, NASA will invest in new ways to develop and infuse autonomous systems into current and future space missions.

Impact to NASA

Autonomous systems are essential to autonomous crew operations, vehicle systems management, rendezvous and docking, and robotics. As humans travel farther from Earth, they will rely on autonomous crew operations to accommodate for communication delays with ground control. Some believe the level of complexity of a crewed deep space vehicle will be similar to that of a nuclear attack submarine, which has 134 crew, whereas space missions in the next few decades will likely carry only four to six crew. Therefore, deep space human exploration missions will require autonomous vehicle systems management to maintain operation of the complex spacecraft and detect and respond to events, such as solar flares and system failures, without crew or ground interference. Missions beyond LEO will also require complete autonomy when conducting rendezvous and docking of spacecraft. Lastly, both exploration and science missions can

Figure 7. The Autonomous Mission Operations project is working to mitigate mission communication time delays.

Source: NASA

Figure 8. The Autonomous Cryogenic Loading Operations project is a current NASA investment to develop autonomous propellant loading technology for future ground and surface systems.

Source: NASA

benefit from autonomous robotics with more complex decision making abilities, including abilities to self-adapt and react to changing environments and situations.

Impact to Nation and Partners

NASA's international partners and other Government agencies have reported autonomous systems as a high priority for investment. Specifically, other Government agencies claimed they could benefit from spinoffs enabling semi-autonomous systems, vehicle safety, and automated traffic management systems. International partners desire advancements in human interaction, mobility, manipulation, autonomous rendezvous and docking, and sensing and perception.

Potential Future Investments

Future investments in autonomous systems will focus on technologies advancing autonomous crew operations, autonomous vehicle systems management, autonomous rendezvous and docking, and autonomous robotics.

Some examples of technologies that could benefit from four years of NASA investment include minimum distance separation software, autonomous planning, self-rover protection, autonomous adapters, sequencing, and autonomous hanger docking, low-impact docking, and grappling capabilities. Future NASA missions will require a stronger integration of flight path and attitude control, highlighting the need for more onboard autonomy.

2012 Investments

NASA currently invests in 21 autonomous systems development projects, with the majority of projects managed by programs in OCT-STP, along with SMD and HEOMD, with development in both low and medium TRLs. These projects include development in crew autonomy beyond LEO, autonomous vehicle systems management, autonomous rendezvous and docking, and autonomous robotics. Of these projects, Satellite Servicing is by far the largest. This project is developing a certified, standardized capability suite of subsystems that will improve technologies necessary for robotic satellite servicing, rescue, and disposal, including rendezvous and docking sensors, docking and capture mechanisms, robotic manipulation, relative guidance algorithms, and power and communication modules. The Autonomous Systems project, also in the Game Changing Development program, aims to develop and demonstrate integrated autonomous systems capable of managing complex operations in space to reduce crew workload and dependence on support from Earth. The AES project, Autonomous Mission Operations, will study the impacts of increasing communication time delays on operations and develop technologies to mitigate these impacts.

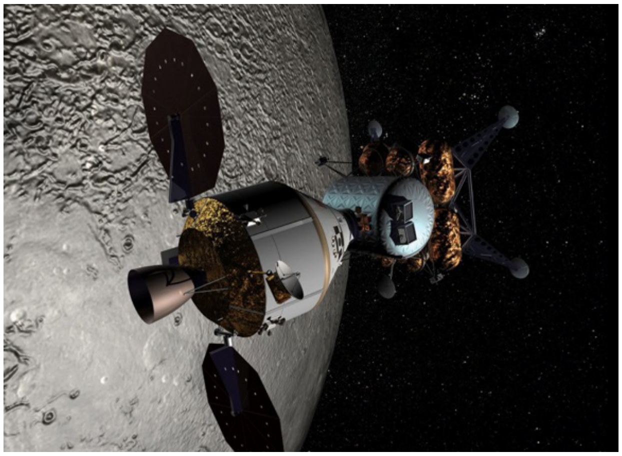


Figure 9. The Autonomous Systems project seeks to automate the operation of habitats and cryogenic loading.

Source: NASA

At least two projects are using the ISS to demonstrate autonomous systems. The Robotic Refueling Mission on the ISS demonstrates and tests the tools, technologies, and techniques needed to robotically service and refuel satellites in space, especially satellites not originally designed to be serviced. The Human Exploration Telerobotics project is conducting demonstrations on the ISS using the Robonaut 2 humanoid robot and the Synchronized Position Hold, Engage, Reorient Experimental Satellites (SPHERES) free-flyers to assist the crew in performing routine or hazardous tasks.

Environmental Control and Life Support System

Technical Challenges and Approach

A reliable ECLSS is critical to all human space missions. Every human space mission, from Project Mercury to the ISS, has relied on an ECLSS, though these systems were often "open loop"—supplementing the life support system with expendables, rather than reusing waste to produce critical elements, such as oxygen, water, and food. As human space missions extend beyond LEO, the logistics of resupply becomes more challenging, thereby maximizing the need for a closed-loop ECLSS. For the next four years, NASA will invest in advancing ECLSS technologies to enable future human space missions with greater safety and efficiency.

Impact to NASA

Further closing the loop on life support systems, including air revitalization, water recovery, waste management, and other habitation capabilities, is necessary for long-duration human missions beyond LEO. Reliability, logistics, and loop closure all contribute to overall mission lifecycle costs and opportunities: the more reliable and resource-efficient an ECLSS is, the farther a mission can safely travel from Earth (and from the option of resupply) and the less mass will have to launch, saving significant costs. Minimizing logistics and designing logistics for repeated reuse will also reduce the amount of waste that requires safe handling, storage, and disposal, both to protect the crew and to satisfy restrictive planetary protection requirements. The integration of microbial-plant systems into life support systems to support air and water purification, waste processing, and crew nutrition could enhance human space exploration. Innovative ECLSS processes can also have crosscutting applications, such as melting used consumables into plastic tiles for radiation protection.[4]

Impact to Nation and Partners

NASA's commercial and international partners have reported ECLSS as a high priority for investment. One commercial partner specifically expressed an interest in waste management technologies.

Potential Future Investments

Future investments in ECLSS technologies will include advancements in air revitalization, water recovery, waste management, and habitation systems, such as food preparation and laundry. More effort is needed to mature technologies associated with trash stabilization, volume reduction, and water recovery from trash and wastes.

Future NASA investment in the next four years could include technologies that target 75 percent oxygen recovery, ECLSS operation under variable cabin pressures, 50 percent water recovery from a diverse wastewater stream that includes hygiene sources, waste stabilization and volume reduction, long-wear clothing, food packaging with a 50 percent reduction, and food production.

One of the ways NASA will test technologies, including ECLSS technologies, is on the ISS. The ISS will provide a valuable test bed for demonstrating the maturation of technologies for air revitalization, water reclamation and management, waste management, and habitation. The ISS will be used to demonstrate capabilities and develop technologies that benefit human and robotic exploration beyond LEO, in keeping with NASA's Strategic Goal 1.1: "Sustain the operation and full use of the ISS and expand efforts to utilize the ISS as a National Laboratory for scientific, technological, diplomatic, and educational purposes and for supporting future objectives in human space exploration."

2012 Investments

NASA currently invests in 30 ECLSS development projects, managed by HEOMD and OCT-STP, with development in both low and medium TRLs. These projects include development in high reliability life support systems, including air revitalization, water recovery, waste management, and other habitation capabilities. Of these projects, the Atmosphere Resource Recovery and Environmental Monitoring project, in the AES program, is the largest. This project focuses on key physico-chemical process technologies for atmosphere revitalization systems and environmental monitoring to increase reliability, capability, and consumable mass recovery, as well as reduce requirements for power, volume, heat rejection, and crew involvement. In the Game Changing Development program, the Next Generation Life Support project aims to develop key life support technologies to enable critical capabilities required to extend human presence beyond LEO and into the solar system. Technologies in this project will focus on increasing affordability, reliability, and spacecraft self-sufficiency, while decreasing mass and enabling long-duration human exploration beyond LEO. The AES Water Recovery Project focuses on the development and demonstration of a water recovery system ground test unit that incorporates and demonstrates functional prototype components for technologies that meet the water recovery needs of future human exploration missions. The AES Logistics Reduction and Repurposing Project seeks to develop technologies that reduce total mission upmass through reuse, repurposing, and reprocessing of crew accommodation items and solid wastes.

Space Radiation Mitigation

Technical Challenges and Approach

Space radiation mitigation was the highest rated technology for human spaceflight in the NRC report. Human missions beyond LEO will require new countermeasures and shielding technologies for space radiation, and developing those technologies requires more specific knowledge and understanding about space radiation and its effects on humans. For the next four years, NASA will invest in technologies such as improved radiation risk assessment models to better understand and predict the effects of radiation, which will influence NASA's concurrent investments in advanced radiation shielding and biological countermeasures.

Impact to NASA

The primary benefit of advancing space radiation mitigation technologies and techniques is increased crew safety, which enables longer duration missions. Improving crew safety depends on a mix of new technologies and techniques, which can include radiation prediction (such as prediction of solar particle events), radiation detection and risk modeling (to monitor local radiation environments), biological countermeasures, and radiation protection technologies (such as advanced materials for shielding or suits). The advancement of one technique or technology can influence another. For example, improving the accuracy of radiation risk modeling can determine the value of certain shielding materials in combination with a biological countermeasure, to determine their overall efficacy in reducing risk. With current models and technologies, the risk of radiation exposure limits missions beyond LEO to three months, but advancements in these techniques and technologies for radiation mitigation could enable extended human missions to the Moon, near-Earth asteroids (NEAs), or Mars. As radiation also impacts sensors and electronics, techniques for predicting high-radiation events and mitigating their effects also improves the survivability of robotic missions.

Impact to Nation and Partners

NASA's international and commercial partners and other Government agencies have reported they could benefit from investment in space radiation mitigation technologies. Commercial partners expressed interest specifically in human protection, and one Government agency cited radiation-hardened devices as a potential benefit.

Potential Future Investments

Investments in space radiation mitigation technology will focus on risk assessment modeling, radiation mitigation, and monitoring technology. Two potential four-year investments in radiation mitigation are biological chemical measures and multifunctional materials and structures for mass-efficient shielding. A potential investment in monitoring technology is warning system onset prediction.

2012 Investments

NASA currently invests in 19 space radiation projects, managed by programs within SMD, HEOMD, and OCT-STP, with development in both low and medium TRLs. These projects include technologies for radiation characterization and monitoring, radiation prediction, radiation risk modeling, biological countermeasures, and radiation protection, including radiation shielding. The RadWorks Project, managed by the AES program, is developing prototypes of advanced, miniaturized radiation measurement technologies, to be placed in integrated vehicle systems. The project is also developing capabilities for a radiation solar particle event storm-shelter. In the Game Changing Development program, the Advanced Radiation Protection project is developing the Integrated Solar Energetic Proton (ISEP) Event Alert Warning System and Monte Carlo Radiation Analysis of Detailed Computer Aided Design Models (MC-CAD). ISEP will address gaps in mitigating the operational impact of solar energetic proton events, while MC-CAD will provide NASA the capability to accurately analyze the radiation shielding performance of current and future space systems. The Coupled System for Assessing the Threat of Solar Energetic Particle Events project, under the SBIR program, is developing a system to help forecasters predict solar particle events and identify “all clear” time periods when there is a low probability of such events occurring. This tool will be a significant step in NASA’s ability to assess the possible impact of solar particle events.

Scientific Instruments and Sensors

Technical Challenges and Approach

Observatory technologies are necessary to design, manufacture, test, and operate space telescopes and antennas that collect, concentrate, and detect photons for astronomy missions. The capabilities of an observatory often dictate the limits of an astronomy mission. Relieving those limits and enabling new missions, such as high-contrast exoplanet imaging, requires innovative observatory technologies, in some cases with an order of magnitude improvement. For the next four years, NASA will invest in observatory technologies with improved performance and angular resolution and reduced weight and cost, so the Agency may expand its knowledge of the universe.

Remote sensing instruments and sensors are components, sensors, and instruments sensitive to electromagnetic radiation, electromagnetic fields, acoustic energy, seismic energy, and other physical phenomenology. This technology is critical to many science missions and some exploration missions. For the next four years, NASA will invest in development of remote sensing instruments and sensors with high efficiency, high resolution, improved durability, and reduced cost and weight.

Impact to NASA

Some essential observatory technologies support both robotic and human exploration missions. Low-mass grazing-incidence optical systems achieving an order of magnitude improvement in spatial resolution will enable advanced future X-ray astronomy missions. Other advancements in observatory technologies such as integrated, adjustable, normal-incidence mirror systems can enable direct imaging of stars and detailed imaging of energetic objects such as active galactic nuclei. One potential exoplanet observatory concept involves the deployment and shape control of a large occulting starshade and formation flying of the starshade relative to the associated telescope. Other techniques for observing exoplanets include interferometry and coronagraphy. Innovations in materials for observatories may enable ultra-stable, large space structures. Regardless of the implementation architecture (segmented or monolithic, active or adjustable, etc.), all future space science missions can benefit from low-cost, low-risk, high-performance space optical systems.

New developments in remote sensing instruments and in-situ sensors can enhance current science missions and enable new ones. Advancing technologies such as single-element and large-array detectors can improve the sensitivity, resolution, speed, and operating temperature needed for many upcoming missions. Innovations in sub-Kelvin coolers and detectors can lead to nearly an order of magnitude improvement in sensitivity and pixel count, enabling new science missions like the study of star formation in galaxies with unprecedented sensitivity and resolution. Increasing the efficiency and life of laser technology, thereby increasing the laser's output power, can enable new Earth science missions, such as profiling Earth's 3D wind field to improve prediction of severe storms. In-situ space sensors that provide accurate measurements of in-situ plasma, fields, and particles will help protect NASA's assets against the adverse effects of space weather. Advancements in electronics, such as high density, high speed, low noise, and low power, can reduce the power, mass, and complexity of remote sensing instruments and in-situ sensors. Electronics that can withstand high radiation and operate in a range of extreme temperatures (-230°C to 125°C) can enable high-performance in-situ measurements on Mars, Titan, the Moon, comets, and asteroids.

Impact to Nation and Partners

NASA's commercial and international partners and other Government agencies have reported they could benefit from investment in observatories and remote sensing instruments and sensors. One commercial partner specifically noted wireless spacecraft as a high priority for investment, and several international partners cited science packages as a high priority. Other Government agencies expressed an interest in a variety of remote sensing technologies, including chemical and biological systems, airborne tracking, Arctic observation, hyperspectral imagery, chemical sensing, advanced chemical characterizations, charge-coupled device development, near-infrared detector deployment, heterogeneous focal planes, and reliable science-based measurement systems.

Potential Future Investments

Investments in observatories will focus on large mirror systems and structures and antennas. Potential large mirror system investments to consider for the next four years are X-ray mirrors, lightweight mirrors, ultraviolet coatings, and segmented mirrors. Some potential structures and antenna investments are passive ultra-stability structures, active ultra-stability structures, and deployable telescopes and booms.

Investments in remote sensing instruments and sensors will focus on developing and advancing detectors and focal planes, micro/radio transceivers/receivers (T/R), and lasers. A potential four-year investment in detectors and focal planes is large format arrays. Investments in micro/radio T/R may include integrated radar T/R and low-noise cryogenic millimeter-wave amplifiers. A potential four-year investment in lasers is a multi-frequency pulsed laser.

2012 Investments

NASA currently invests in 38 observatories projects, managed by programs within SMD and OCT-STP, with development in both low and medium TRLs. These projects develop technologies to design, manufacture, test, and operate space telescopes and antennas. The Exoplanet Direct Imaging project, managed by the Astrophysics Research and Analysis program, is developing high-contrast coronagraphic techniques for segmented telescopes to enable direct imaging of exoplanets from space. Also in the Astrophysics Research and Analysis program, the Fabrication of High Resolution Lightweight X-ray Mirrors Using Mono-Crystalline Silicon project is developing an X-ray mirror fabrication method that will enable the production of mirror segments with increased angular resolution and more effective area per unit mass.

NASA currently invests in 161 remote sensing instruments and sensor projects. Programs within SMD and OCT-STP manage these projects, including the Astrophysics Research and Analysis program, the Center Innovation Fund, the Earth Science Technology Office (ESTO), Goddard Space Flight Center Internal Research and Development (IRAD) activities, SBIR, the Small Business Technology Transfer (STTR) program, and the Space Technology Research Grants program. The projects develop low- and medium-TRL technologies for components, sensors, and instruments sensitive to electromagnetic radiation and other physical phenomenology. Under the Astrophysics Research and Analysis program, the New Detector Development for X-ray Astronomy project is developing, building, and testing a new type of active pixel detector, which could be employed in future missions. The Coronagraphic Planet Finding with Energy Resolving Detectors project, managed by the Space Technology Research Grants program, is building a 10,000 pixel Microwave Kinetic Inductance Detectors camera to integrate with a coronagraph, adaptive optics system, and telescope to become the first visible through near-infrared planet-finding coronagraph. The

Structured Non-Linear Optical Materials for LIDAR-based Remote Sensing project, managed by the STTR program, is developing a domain-engineered magnesium-oxide-doped lithium niobate for LIDAR-based remote sensing and communication applications.

Entry, Descent, and Landing

Technical Challenges and Approach

Entry, descent, and landing (EDL) technologies, including thermal protection systems (TPS) and other component technologies, are necessary for landing human and robotic missions on planetary bodies and for human return to Earth. EDL TPS consist of materials and systems designed to protect spacecraft from extreme high temperatures and heating during entry, descent, and landing phases. Other EDL technologies encompass the components, systems, qualification, and operations to safely bring a vehicle from approach conditions to contact with the surface of a solar system body or to transit the atmosphere of the body. EDL technologies have to be designed for specific atmospheres to enable specific missions. For example, a human mission to the surface of Mars has inherent, distinctive EDL challenges. The current capability to deliver payloads to the surface of Mars within a small landing ellipse is inadequate for future mission needs. The current state of the art can deliver 1.5 metric tons (mT) to Mars (demonstrated with the Mars Science Laboratory (MSL) mission), but human exploration of Mars will require 10's of mT capability. In addition, rigid TPS—the current state of the art for EDL TPS—are constrained by the launch vehicle shroud diameter, currently at scaling limit. Mars EDL systems require a deceleration system to be used supersonically (deployed at a higher altitude) to increase payload mass and improve targeting. A new EDL architecture, including TPS and other component technologies, will provide the necessary capability for future human missions to Mars as well as other future human and robotic missions. For the next four years, NASA will develop EDL technologies to improve maintainability, reduce system size and mass, and increase system robustness.

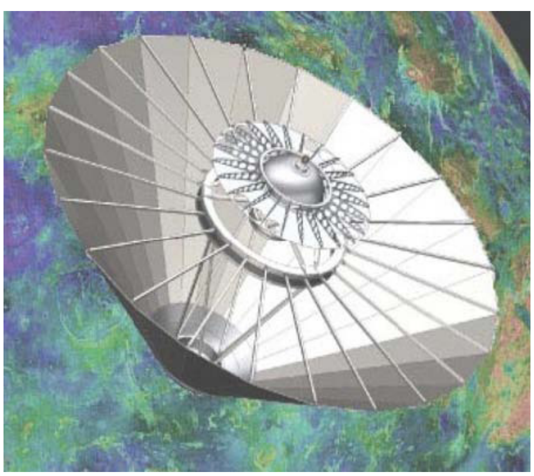


Figure 10. The Deployable Aeroshell Concepts and Conformal TPS project is developing a mechanically deployed low ballistic coefficient entry system architecture and high strain-to-failure TPS for reliable thermal protection.

Source: NASA

Impact to NASA

EDL TPS is mission critical for future human and robotic missions that require planetary entry or reentry, including every mission for return-to-Earth. The benefits of EDL TPS technologies are enabling missions, reducing system mass, and increasing system reliability. For example, a TPS with lighter, cheaper, smaller, more robust, environmentally friendly insulation materials could save precious spacecraft weight, thereby increasing performance and payload capacity. Ablative materials enable NASA missions that require high-mach-number reentry, such as NEA visits and Mars missions. Large entry heat shields may provide enabling means to increase landed mass on planetary surfaces.

Advancements in other EDL technologies will enable future robotic missions to destinations such as asteroids, comets, Venus, Mercury, Mars, icy moons, the gas giant planets, Titan, and others. The key performance characteristics that EDL technology developments will target are delivery and performance reliability, cost, delivered mass, landing site access, and landing precision. Low cost is enabled by improved simulation and ground-to-flight extrapolation. Both precision landing and hazard avoidance are enabled by a combination of more advanced terrain sensing and more capable algorithms to divert the lander to the desired target. If entry, descent, and landing at a destination involves multiple transitions, advanced avionics could guide the spacecraft or payload as it passes through each transition, improving mission safety. In general, the benefits of focused EDL technology activities include increased mass delivery to a planet surface, increased planet surface access, increased delivery precision to the planet's surface, expanded EDL timeline to accomplish critical events, increased robustness of landing system to surface hazards, enhanced safety and probability of mission success for EDL phases of atmospheric flight, human safety during return from missions beyond LEO, and sample return reliability and planetary protection.

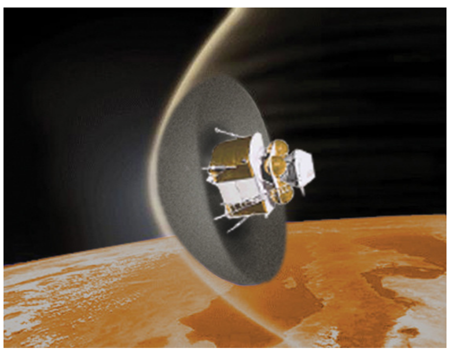


Figure 11. The Regolith-Derived Heat Shield for Planetary Body EDL with In-situ Fabrication project proposes to develop entry heat shields with regolith of moons and asteroids.

Source: NIAC, Hogue

Impact to Nation and Partners

NASA's commercial and international partners have reported EDL technologies as a high priority for investment. One commercial partner claimed it could benefit specifically from development in deployable hypersonics and attached deployable decelerators. Another commercial partner specifically expressed an interest in rigid TPS and flexible TPS.

Potential Future Investments

Four EDL TPS technologies to consider for NASA investment over the next four years are obsolescence-driven TPS; reusable TPS; rigid ablative TPS with a desired performance parameter of less than 11 km per second (km/s); and inflatable, flexible, and deployable TPS.

Investments in other EDL technologies will focus on the components, systems, qualification, and operations that make entry, descent, and landing possible. For example, one major component of EDL technologies is decelerators, which can be rigid or deployable. Potential four-year investments in deployable decelerators include hypersonic inflatable aerodynamic decelerator (HIAD) control and scalability, mechanical deployable scalability, and advanced flexible structures. Another major system enabling EDL technologies is guidance, navigation, and control (GNC). Potential four-year investments in GNC technologies include adverse event triggers and algorithms, terrain and hazard sensors, terrain tracking, and hazard detection.

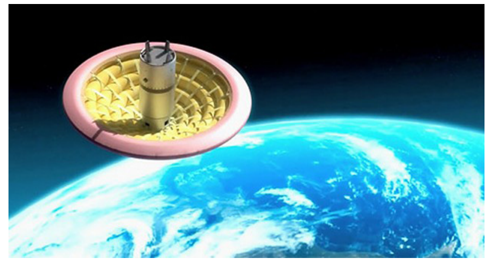


Figure 12. The HIAD project is developing an entry and descent technology to enhance and enable robotic and scientific missions to destinations with atmospheres.

Source: NASA

EDL technologies also rely on investments in modeling and simulation of entry, descent, and landing scenarios. Potential four-year investments in entry modeling and simulation include advanced fluxes, unstable computational fluid dynamics, Mars radiation models, and tight coupling. Potential four-year investments in descent and landing modeling and simulation include static fluid structure interaction and ground-surface plume interaction models. Investment in new modeling techniques, improved physical models, and quantified uncertainty estimation must be ongoing and must be conducted in conjunction with validation experiments utilizing ground test facilities capable of producing flight-relevant conditions. In contrast, the development of modeling techniques and tools in the absence of application is not within the scope of technology programs.

2012 Investments

NASA currently invests in 24 EDL TPS projects, all of which are managed by programs within OCT-STP, with development in both low and medium TRLs. These projects include the development of materials and systems designed to protect spacecraft from extreme high temperatures and heating during entry, descent, and landing, and include technologies for heat shields and rigid and flexible TPS. The Low Density Supersonic Decelerators project, managed by the Technology Demonstration Missions program, will conduct full-scale, stratospheric tests of breakthrough technologies in supersonic inflatable aerodynamic decelerators and develop a 30-meter-diameter parachute. Under the Game Changing Development program, the Hypersonic Inflatable Aerodynamic Decelerator project will develop and demonstrate hypersonic inflatable aeroshell technologies suitable for an ISS downmass capability. The Deployable Aeroshell Concepts and Conformal TPS project, also managed by the Game Changing Development program, is developing a low ballistic coefficient aeroshell system of woven carbon cloth stretched over a mechanically deployable ribbed structure. This breakthrough capability is designed to deliver entry system payloads to the most challenging of mission destinations. The Woven Thermal Protection Systems program, also in the Game Changing Developments program, is working on an advanced, 3D weaving approach for the design and manufacturing of thermal protection systems.

In addition to EDL TPS investments, NASA currently invests in 14 other EDL technology projects, managed by HEOMD and OCT-STP, with development in low, medium, and high TRLs. These projects include developments in components, safety, qualification, and operations to safely bring a vehicle from approach to contact with the surface or atmosphere of a solar system body. This theme

Figure 13. The ALHAT project seeks to develop planetary landers that can automatically recognize a landing site, assess potential landing hazards, and adjust accordingly during descent.

Source: NASA

includes precision landing and hazard avoidance, deployable hypersonics, and deployable decelerators. The Autonomous Landing and Hazard Avoidance Technology (ALHAT), supported by AES and the Technology Demonstration Mission program, is developing advanced technologies vital to achieving autonomous landing and hazard avoidance, including surface-tracking sensors. The Morpheus Vertical Test Bed (VTB)/ALHAT project, managed under the Advanced Exploration Systems program, will fly a reusable Morpheus VTB with integrated ALHAT systems to demonstrate realtime hazard detection and avoidance. The project aims to develop technologies integrated with capabilities that can be adapted to human spaceflight mission architectures. The MSL Entry Descent and Landing Instrumentation project, also included in the Technology Demonstration Mission program, is a set of engineering sensors designed to measure the atmospheric conditions and performance of an entry vehicle's heat shield during atmospheric entry and descent.

Adjacent Technology Investments

Adjacent technologies are a significant focus of technology investment and will comprise at least 20 percent of the Agency's technology investment over the next four years. A full list of Adjacent technology investments are shown in Table 3. Though not part of the Core, these Adjacent investments are still high priority and integral to supporting the strategy outlined by the NASA SSTIP, while also ensuring NASA meets NRC-recommended technology investment priorities. They are Adjacent in the sense that they are closely related to and can benefit from the Core investments.

Potential Adjacent technology investments might include investments related to thermal control, crew health, energy generation, and nanotechnologies. Adjacent technology investments also include investments in support of collaboration with other Government agencies such as cybersecurity, structural monitoring, and vehicle safety technologies. Many of these technologies are also applicable to national goals and priorities, such as cybersecurity and nanotechnology, which were specifically addressed in the Science and Technology Priorities for the FY 2014 Budget memorandum. Three Adjacent technologies—power generation, thermal control systems, and long-duration crew health—are associated with the NRC's top 16 priorities. These are discussed in more detail below.

Power Generation

Every NASA mission requires power, and as missions become more complex, longer, and farther from Earth and the sun, new developments in power generation become critical. Improvements in power generation systems might include greater efficiency, reduced weight, and increased durability. These improvements could increase the capabilities of current missions and enable new science and exploration missions far beyond LEO.

With advancements that reduce weight and increase efficiency, new power generation technologies can remove limitations on current missions, for example, extending science probe missions farther from the sun or planning larger systems into human exploration missions, such as in-situ resource utilization (ISRU) plants. Advancements in durability have many potential benefits for NASA missions. Power generation systems that can survive extreme temperatures can enable surface missions to Venus and the polar regions of the Moon and Mars, and tolerance for high radiation and low intensity/low temperature conditions could enable missions to the outer planets. Miniaturization of power generation systems can both improve impact tolerance for landing surface missions and also enable nanosatellites. Studies by the Glenn Research Center show that current power systems compose 20 to 30 percent of spacecraft mass, and about one-third of

Technology Investment Classification	Associated NASA SSTIP Technical Challenge Area	Related Level 2 TABS	Associated NRC High Priorities (Top 16 in Bold)
Adjacent	Advanced Power Generation, Storage, and Transmission; Increased Available Power	3.1	**Solar Power Generation (Photovoltaic and Thermal); Fission Power Generation;** Radioisotope Power Generation
Adjacent	Advanced Power Generation, Storage, and Transmission; Increased Available Power	3.2	Batteries
Adjacent	Advanced Power Generation, Storage, and Transmission; Increased Available Power	3.3	Power Distribution and Transmission; Power Conversion and Regulation
Adjacent		5.3	Adaptive Network Topology
Adjacent	Efficient Accurate Navigation, Positioning, and Timing	5.4 (except 5.4.3)	Timekeeping and Time Distribution
Adjacent	EVA	6.2	Extravehicular Activity Portable Life Support System; Extravehicular Activity Pressure Garment
Adjacent	Long-Duration Health Effects	6.3	**Long-Duration Crew Health**
Adjacent		6.4	Fire Detection and Suppression; Fire Remediation
Adjacent	Surface Systems	7.1 (7.1.2, 7.1.3, 7.1.4)	ISRU Resource Acquisition; ISRU Products/Production; ISRU Manufacturing/Infrastructure, etc.
Adjacent	Surface Systems	7.2	Food Production, Processing, and Preservation; Autonomous Logistics Management; Maintenance Systems
Adjacent	Surface Systems	7.3	Surface Mobility
Adjacent	Surface Systems	7.4	Smart Habitats; Habitation Evolution
Adjacent	Surface Systems	7.6	Construction and Assembly; Dust Prevention and Mitigation
Adjacent	Nanotechnology	10.2	Energy Generation (Nano)
Adjacent	Nanotechnology	10.3	Nanopropellants
Adjacent	Nanotechnology	10.4	Sensors and Actuators (Nano)
Adjacent	Improved Flight Computers	11.1	Flight Computing; Ground Computing
Adjacent	Modeling and Simulation	11.2	Science Modeling and Simulation
Adjacent	Modeling and Simulation	11.3	Distributed Simulation
Adjacent		12.3 (12.3.1, 12.3.4, 12.3.5)	Deployables, Docking, and Interfaces; Mechanisms: Design and Analysis Tools and Methods; Mechanisms: Reliability/Life Assessment/Health Monitoring
Adjacent		12.4 (12.4.2)	Intelligent Integrated Manufacturing and Cyber Physical Systems
Adjacent		12.5 (12.5.1)	Nondestructive Evaluation and Sensors
Adjacent	Cryogenic Thermal Management	14.1, 14.2	**Active Thermal Control of Cryogenic Systems**

Table 3. Adjacent technology investments.

that is attributed to power generation systems. Developments in lighter and more powerful solar arrays or cost-effective and lightweight nuclear systems could reduce launch costs or save mass for other systems, such as science instruments and exploration tools.

NASA currently invests in 25 space power generation projects, which include technologies for chemical, solar, radioisotope, fission, and fusion power, including the development of fuel cells and solar arrays. Potential investments for the next four years include high-performance photovoltaic arrays and two kilowatt end-to-end fission. Solar power generation, including photovoltaic and thermal, and fission power generation were two of the NRC's top 16 priorities.

Thermal Control Systems

Thermal control systems are necessary for all space missions. These systems maintain an appropriate temperature range in all vehicle surfaces and components through the changing heat loads and thermal environments of different mission phases. Effective thermal control systems provide three basic functions to the vehicle or system design: heat acquisition, heat transport, and heat rejection. Improvements could increase the reliability and efficiency and reduce the mass and weight of thermal control systems.

The primary benefits of thermal control technologies are enabling missions, reducing system mass, and increasing system reliability. Radiators are mission-critical for many proposed missions. To reduce radiator mass, area, and pumping power, research is needed on lightweight radiators or compact storage systems for extending extravehicular activity (EVA) capability. The use of micro-channel fabrication techniques or composite materials can enable higher efficiency and lower mass designs. The development of single-loop architectures could save significant weight, reduce system complexity, and increase reliability of the thermal design of crewed systems.

NASA currently invests in 19 thermal control systems projects, which include technologies for heat acquisition, heat transport, and heat rejection, as well as active and passive thermal control. Potential investments for the next four years include ground-to-flight insulation systems, high flux cooling with precise temperature control, evaporative cooling technologies, and a variable heat rejection radiator. The NRC specifically rated active thermal control of cryogenic systems as one of the top 16 priorities for NASA investment.

Long-Duration Crew Health

Long-duration crew health includes a variety of technologies and techniques to maintain the physical and behavioral health of the crew and sustain optimal performance throughout the duration of a mission. Future human space missions will challenge crew more than ever before, with longer periods in the extreme environment of space and far from familiar surroundings. Sustaining crew health and performance is not only an essential safety factor for human missions, but it is also critical for the success of the mission itself, as a human crew is just as much a vital component to human space missions as the spacecraft that carries them.

Improvements in long-duration crew health techniques and technologies could provide increased safety and productivity of human space missions.

Long-duration crew health technologies could enhance future human space missions by selecting an optimal crew with preliminary medical screening, maintaining physical and behavioral crew health and performance with in-space diagnoses and effective countermeasures, and preparing crew for extreme medical situations, such as surgery. Pre-flight and in-space research could contribute to medical breakthroughs for long-duration missions, such as artificial gravity. Monitoring technologies, training methods, and other metrics and tools could both contribute to research and also help prepare crew for new missions and their challenges. The challenges of space exploration will become more complex as the missions become more complex, such as physical trauma from surface exploration or psychological issues caused by isolation for months on end, but a wide variety of long-duration crew health technologies can help plan for these challenges and prepare solutions.

NASA currently invests in 23 human health and performance projects, which include technologies for medical screening, long-duration spaceflight medical care and behavioral health, in-space diagnostic and treatment capabilities, and effective countermeasures. Potential investments for the next four years include wearable computing and biomedical sensors, alternative non-exercise countermeasures, artificial gravity prescription devices, and a virtual therapist. The NRC included long-duration crew health among its top 16 priorities.

Complementary Technology Investments

Complementary technology investments represent opportunities to invest broadly, albeit at a low level, in an effort to avoid missing an opportunity that may someday form part of NASA's Core investments. These technologies will comprise 10 percent of the Agency's technology investment over the next four years but are not to be confused with the low-TRL investment that also happens to be at the 10 percent level. Complementary technologies may be of any TRL. Examples of Complementary technologies that were outlined in the NRC report but not ranked as high-priority are discussed below.

Advanced (TRL<3) In-space Propulsion Technologies include technologies like beamed energy, high energy density materials, antimatter, and advanced fission propulsion. While the NRC considers these technologies "game-changing," they are unlikely to occur in the next 20 years. The NRC recommended that these and other low-TRL, very-high-risk technologies be provided a low level of funding, making them Complementary technologies.

Some information technologies, including semantic technologies, intelligent data understanding, and collaborative science and engineering, are considered Complementary investments. While they can provide improvements and benefits over current information technologies, the NRC noted that much of the development of these technologies is being done now by industry. The inclusion of these technologies in the Complementary category stems from the low level required of NASA investment, not TRL.

Launch and ground processing technologies are also Complementary. The primary benefit from advancements in these technologies is reduced costs, not technological capabilities in a direct way. Current technologies in this area are significant contributors to mission lifecycle costs, including those supporting:

- Transportation, assembly, integration, and processing of the launch vehicle, spacecraft, and payload hardware at the launch site, including launch pad operations.
- Launch processing infrastructure and its ability to support future operations.
- Range, personnel, and facility safety capabilities.
- Launch control and landing operations, including weather and recovery for flight crews, flight hardware, and returned samples.
- Mission integration and control center operations and infrastructure.
- Environmental impact mitigation for ground and launch operations.

Ground and launch systems processing includes several challenges, such as reducing the cost of maintaining and operating ground control and launch infrastructure, improving safety, and improving the timeliness, relevance, and accuracy of information provided to ground control and launch personnel. The NRC noted that advanced technology can contribute to solving these challenges, but recommended that management practices, engineering, and design would be more effective means for addressing improvements.

Complementary technologies are the pioneering and crosscutting technologies in the NASA SSTIP pillars (discussed below) that were neither in the NRC's 16 top priorities nor the NRC's 83 high priorities. These technologies were consistently determined, by the NRC, to have the potential for only minor improvements in mission performance, lifecycle cost, or reliability, but are still considered widely used and important to future NASA programs and missions.

Pillar 1: Extend and sustain human presence and activities in space

Goal Summary

Human exploration in space has been a key focus of NASA since the Agency formed in 1958. From the earliest Mercury missions, to the Apollo missions and Moon landings, to astronauts on the ISS today, NASA has always pursued new knowledge on how humans can live, work, and travel in space. This knowledge often reveals new challenges, such as the dangers of radiation exposure, physiological responses to microgravity, and psychological issues in constrained environments. NASA responds to these challenges by researching techniques to protect and increase human health and performance in space and on planetary surfaces and by discovering, developing, and testing new technologies for deployment in the spacecraft and its support systems.

NASA is planning a capability-driven approach to achieve proficiency in space operations in and beyond our Earth-Moon system, and then explore multiple deep space destinations. Mission analysis and international discussions supporting these efforts are ongoing. NASA will develop the capabilities to reach—and operate at—a series of increasingly demanding destinations, while advancing technological capabilities with each step forward. This plan includes early test and demonstration activities in cis-lunar space as specified in the 2010 NASA Authorization Act. NASA's ultimate destination for human exploration in the next half century is Mars.

Capability Objectives

The President and Congress recognized that core transportation elements, key systems, and enabling technologies are fundamental investments required for human exploration beyond LEO. These investments will provide the foundation for the next half-century of American leadership in space exploration.

To achieve this goal of extending and sustaining human presence and activities in space, NASA must invest in technologies enabling four capability objectives:

- Achieve improved spacecraft system reliability and performance.
- Enable transportation to, from, and on planetary bodies.
- Sustain human health and performance.
- Enable payload delivery and human exploration of destinations and planetary bodies.

These capabilities will make it possible for humans to safely and efficiently travel, live, and explore in space and on distant destinations.

GOAL 1

EXTEND AND SUSTAIN HUMAN PRESENCE AND ACTIVITIES IN SPACE

1. Achieve improved spacecraft system reliability and performance
    - Long-duration ECLSS
    - Lightweight space structures and materials
    - Advanced power generation, storage, and transmission
    - Autonomous systems
2. Enable transportation to, from, and on planetary bodies
    - Launch ground systems
    - Launch propulsion systems
    - High power in-space propulsion
    - Advanced EDL
3. Sustain human health and performance
    - Space radiation mitigation
    - Long-duration health effects
4. Enable payload delivery and human exploration of destinations and planetary bodies
    - EVA
    - Surface systems

Achieve Improved Spacecraft System Reliability and Performance

From the spacecraft structure to the life support systems, human space missions require an integrated and reliable set of systems to safely and efficiently live and work in space. The next generation of human space exploration will depend on innovations in a long-duration ECLSS. The ECLSS provides the critical resources humans need to survive, including oxygen, water, and food, as well as maintaining a suitable thermal and atmospheric environment within the spacecraft. The ECLSS also relates to logistics, managing the processing of waste and recycling of used materials. Current ECLSS technologies can support a crew on the ISS, but the system relies on constant resupply of resources, which will be impractical and unsafe for missions traveling far from Earth. A future ECLSS will first concentrate on increased reliability and then will continue to further "close the loop" on resources, by recycling, reusing, and producing most if not all of the crew's necessary resources.

Other necessary innovations supporting future human and robotic space missions are lightweight space structures and materials; advanced power generation, storage, and transmission systems; and autonomous systems. Innovations in lightweight space structures and materials could reduce the cost of launch and propulsion without losing the advantages of protection from radiation and MMOD. Advanced energy technologies are necessary to power the large, integrated systems needed to support human missions, such as the ECLSS and crew habitat. As the NRC noted, power must not be the limiting resource for future missions far from earth.

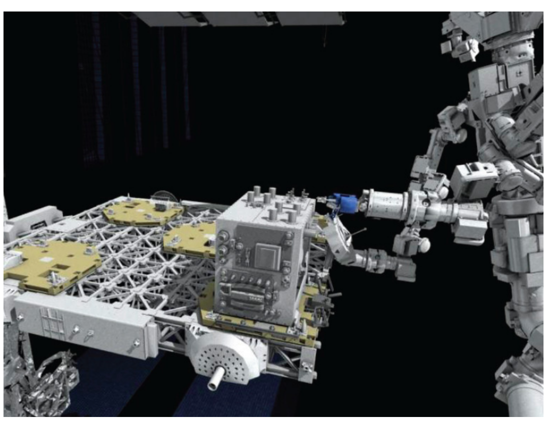


Figure 14. The Satellite Servicing project is developing a capability suite of autonomous subsystems to service satellites with robots or human-robotic teams.

Source: NASA

Crewed spacecraft must be able to survive for long periods of time, while potentially facing solar storms or sub-system failures, without input from terrestrial control centers or operators.

Future human missions, especially missions into deep space, must rely on advanced autonomous systems to help the crew manage the complex spacecraft and systems.

Enable Transportation To, From, and On Planetary Bodies

Historically, the highest risk in human space flight has been in the ground, launch, and reentry periods of space missions. Therefore, increasing mission safety and performance demands improvements in launch ground systems, launch propulsion, and advanced EDL. Improvements in launch ground systems will help missions run more efficiently and affordably, which becomes more important as new missions demand specific launch windows, such as missions to a NEA. More efficient ground and launch processing systems must reduce the overall mission lifecycle cost, to enable NASA to meet its mission within the constrained budget environment. Innovations in launch propulsion technologies must send more mass to orbit more affordably, enabling missions with larger systems, such as the large ECLSS and habitat systems needed for human missions. Advanced EDL technologies will be designed for specific atmospheric environments, so the crew will be able to land safely at their destination with critical supplies and technologies, such as rovers and habitat systems, intact.

The speed in which a space mission reaches and returns from its destination affects most missions but is most important for human missions. The less time a human crew is in space, the less they are exposed to the risks of the space environment, such as radiation and microgravity. Potential deep space destinations of future human missions, such as NEAs and Mars, require months of travel. High-power in-space propulsion systems can decrease that time and increase the safety and productivity of human space missions. Such systems can also enable prepositioning of vital resources for the crew.

Figure 15. The Low Density Supersonic Decelerators project is one of NASA's current projects developing EDL TPS technologies.

Source: NASA

Sustain Human Health and Performance

There are many challenges to protecting the human body in the space environment. Any human living beyond the protection of the Earth's atmosphere risks exposure to dangerous amounts of radiation, which can lead to debilitating or potentially fatal diseases, such as cancer. Living in microgravity for long periods of time can also cause problems, such as loss of bone density. These concerns have limited the duration of crewed missions in LEO. Exploration on lunar or planetary bodies bring additional challenges, such as fine, abrasive dust that can damage the human respiratory system. Other issues include extreme high and low temperatures and the inaccessibility of oxygen, water, and food sources. In addition to these physical risks are the psychological challenges of living in isolation in a vast but confining area, far from familiar surroundings and loved ones. These and other challenging aspects inherent to space travel can test an astronaut's mental well-being and negatively impact performance.

Figure 16. The Habitat Systems project delivers concepts for lightweight, safe, and reliable exploration habitats capable of supporting humans living and working in space and on planetary bodies.

Source: NASA

Innovations in space radiation mitigation and long-duration health effects should decrease the risks of living and working in space and improve astronaut performance. A wide variety of technologies and systems comprise an effective space radiation mitigation plan. One example is shielding materials that are light enough to launch affordably and designed to protect against solar particle events. Space weather modeling and simulation tools can help astronauts and ground control predict and prepare for dangerous solar events, such as sudden radiation blasts from large solar flares. Physical countermeasures, such as anti-radiation medication, can also support a comprehensive radiation mitigation plan. Techniques and technologies for long-duration health effects are similarly diverse, ranging from pharmaceuticals to support weakened immune systems to whole spacecraft designed to produce artificial gravity. These developments will build upon research conducted since humans first entered space and will also require new research projects planned well into the future, so scientists and innovators can first understand the health issues astronauts may face and then devise ways to counteract these effects.

Enable Payload Delivery and Human Exploration of Destinations and Planetary Bodies

Future human space missions will seek new destinations that provide many new opportunities for discovery but also many new challenges. For example, a NEA mission may require astronauts to explore a surface without being able to walk on it, and the sheer distance between Earth and Mars is an intimidating challenge for planning resource logistics. To meet these challenges, human missions will require innovations in EVA systems and surface systems.

EVA systems include the spacesuit, portable life support system (PLSS), power and avionics, and tools an astronaut needs to work outside a habitat, either in space or on the surface of a planetary body. Like habitats and life support systems, EVA systems have to provide a constant supply of oxygen, water, power, and a communications system while protecting the astronaut from exposure to the space environment, including radiation, extreme temperatures, and on the surface of a destination, dust and other possible contaminants. Current EVA systems are cumbersome and depend on consumables, limiting an astronaut's mobility and length of excursions. Future systems must alleviate these issues, so astronauts can explore and work in space safely, productively, and for longer periods of time.

Innovations in surface systems should extend the time and areas human missions can explore on a lunar or planetary surface. The longest time a single Apollo mission spent on the surface of the Moon was three days, and the locations were restricted to near the equator. With improved habitats, rovers, and spacesuits to protect the crew from the harsh environment, the crew can explore larger or more difficult areas, such as the lunar poles. With ISRU systems to produce critical resources, astronauts can safely and productively explore destinations long enough to conduct more meaningful science and expand human knowledge of space. Surface systems for missions to Mars will need to comply with planetary protection requirements.

Pillar 2: Explore the structure, origin, and evolution of the solar system, and search for life past and present

Goal Summary

The history of the formation of our solar system and its diverse planetary bodies is being uncovered by NASA and its partners not only through remote observations but also by the activities and return samples of robotic and human missions. For example, the early bombardment history of the inner solar system was initially revealed in the study of lunar samples returned from the Apollo missions. The Genesis, Stardust, and Hayabusa robotic sample return missions have revealed new information about the sun, comets, and asteroids. The story of our own solar system can become more fully known with additional detailed geologic study of the surface, subsurface, and interior of planetary bodies.

The search for evidence of past or present life and the implications for human habitability of environments beyond Earth is a research priority with broad scientific and general interest. The presence of water, organic material, and energy represent three concurrent indicators in the search for signs of life as we understand it now. The detection of water in a wide variety of solar system locations, including the Martian surface, the moons of the giant planets, Earth's Moon, and small bodies—such as comets and asteroids—has broadened the search for indications of life. The diversity of these locations and the known complexity of biotic and pre-biotic chemistry mean that advanced instrumentation is required and direct examination of samples, either returned to Earth or in situ by robots or humans, is needed to produce definitive results.

Near-Earth asteroids (NEAs) and Mars are both compelling destinations for in-situ analysis. Many asteroids are primitive solar system bodies; that is, they exist largely unchanged from the earliest period of initial solar system formation. As the 2011 planetary science decadal survey noted, "These objects provide unique information on the solar system's origin and early history and help researchers to interpret observations of debris disks around other stars." Mars also has the potential to advance scientific understanding of the solar system. The NASA decadal survey "Visions and Voyages for Planetary Science in the Decade 2013-2022" states

Figure 17. Featured in this artist's concept is the MSL Curiosity rover, which is now on Mars to determine the potential for life on the red planet in the past, present, or future.

Source: NASA

that “Mars has a unique place in solar system exploration: it holds keys to many compelling planetary science questions, and it is accessible enough to allow rapid, systematic exploration to address and answer those questions.”

In-situ space measurements are also important for comprehending the future of Earth. Comparative planetology—for example, understanding why Venus, Earth, and Mars all evolved in different directions and exhibit vastly different abundances of water and carbon—is key to understanding how the Earth might be expected to change over long time scales in the future. On both the near- and long-term time scales, characterizing and understanding the population, sizes, and orbit characteristics of NEOs is essential to detecting and mitigating potential hazards to Earth. NASA can approach these and many other questions by developing technologies to travel to places of interest, perform analyses and measurements in situ, and in some robotic and all human missions, return samples to Earth for further analysis.

GOAL 2

EXPLORE THE STRUCTURE, ORIGIN, AND EVOLUTION OF THE SOLAR SYSTEM, AND SEARCH FOR LIFE PAST AND PRESENT

1. Achieve improved spacecraft system reliability and performance
    - Advanced power generation, storage, and transmission
    - Lightweight space structures and materials
    - High-bandwidth communications
2. Enable transportation to, from, and on planetary bodies
    - Launch propulsion systems
    - High power in-space propulsion
    - Efficient accurate navigation, positioning, and timing
    - Advanced EDL
3. Enable advanced in-situ measurement and exploration
    - Life detection
    - Robotic maneuvering, manipulation, sensing and sampling
    - Autonomous rendezvous and dock
    - Nanotechnology
    - Advanced sensors (all types of detecting sensors: geological, chemical, etc.)

Capability Objectives

To achieve this goal, NASA will invest in technologies enabling three capability objectives:

- Achieve improved spacecraft system reliability and performance.
- Enable transportation to, from, and on planetary bodies.
- Enable advanced in-situ exploration.

These capabilities will make it possible for human and robotic missions to travel to different areas of the solar system where they can conduct measurements, analysis, and sampling to expand our knowledge of the solar system and search for evidence of and potential for life.

Achieve Improved Spacecraft System Reliability and Performance

Several individual and integrated space systems can either limit or enhance a mission’s potential. Every space mission requires power. The performance and weight of power generation, storage, and transmission systems influence the possible distance, duration, and productivity of a mission. Similarly, the weight of the space structure itself can be a limiting factor. The data rate of the communications system can limit the amount of data the mission can transmit to Earth and the speed of the transmission.

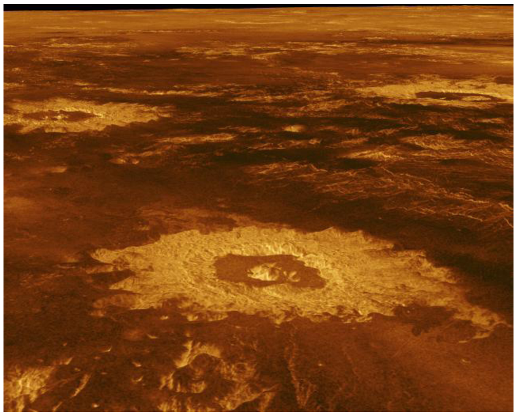


Figure 18. Operating on the surface of Venus requires technologies that can withstand temperatures around 460°C and 92 bars of pressure. In the other extreme, surface missions on a polar night on Mars would have to survive temperatures as low as -128°C.

Source: NASA, Magellan Spacecraft

These limitations can be reduced or effectively removed with innovations in new technologies. Advanced power generation, storage, and transmission systems can be lighter, more efficient, and provide higher performance, so missions can travel farther and longer, to perform in-situ analysis on destinations previously thought unreachable. Advanced power systems can also have increased durability, enabling in-situ analysis in extreme environments, such as the high temperatures of Venus or the low temperatures of the Martian polar regions. Lightweight space structures and materials save on launch mass and can enable missions with larger, more powerful science instruments or crewed missions, which require large life support systems and a habitat. High-bandwidth communications can vastly increase the rate at which a mission in space or on a planetary surface can transmit data to ground control as well as receive guidance from ground control. Working with advanced information processing systems, communication innovations can greatly improve the extent and quality of transmitted data and thus improve the quality of the science.

Enable Transportation To, From, and On Planetary Bodies

The hardware that does in-situ sampling and analysis requires transportation to the site being sampled and analyzed. This requires launch propulsion systems to get robotic payloads or a human crew off Earth and into space; an in-space propulsion system to get to the destination; and position, navigation, and timing (PNT) technology to guide the spacecraft as it travels through space. Finally, EDL technology is needed to get the payload or crew to the surface of the destination.

Innovations in these technologies can enhance missions conducting in-situ measurements. New launch propulsion systems can increase the amount of mass that can affordably launch to space, allowing for larger, more powerful science instruments or increased energy and fuel storage enabling travel over longer distances. High-power in-space propulsion can also enable missions to travel farther and enable larger spacecraft to travel far from the sun, a prime energy source for most space missions. Efficient and accurate PNT together with onboard

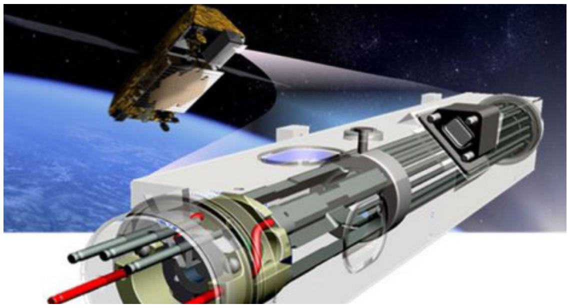


Figure 19. The Deep Space Atomic Clock project will fly and validate a miniaturized, ultra-precise mercury-ion atomic clock for precision navigation.

Source: NASA

guidance and control can enable complex orbital maneuvers and precise landings. Advanced EDL technologies must protect highly sophisticated instruments and a human crew through a variety of atmospheric environments.

Enable Advanced In-situ Measurement and Exploration

Innovations in instruments and sensors can enhance the quality and variety of possible in-situ measurements. Devices for life detection can search for the presence of the "building blocks of life," such as oxygen, water, and organic compounds, to determine the possibility of life existing now, existing in the past, or being sustained in the future, such as a human colony. Other advanced sensors can perform geological, chemical, magnetic, seismic, and other measurements to assess the different characteristics of the explored site. Advancements in robotics can increase the accessibility of in-situ measurements and sampling, for both crewed and uncrewed missions. Robots that can maneuver on, over, or under extreme terrain and manipulate the surface for sampling can enable in-situ analysis in unexplored territory, such as places inaccessible to previous rovers or human explorers or whole new destinations, like beneath the icy crust of Enceladus or Europa. Lastly, nanotechnology developments can enhance all of these systems, by decreasing their overall weight, increasing their tolerance to radiation and other damage, lowering their power requirements, increasing their resolution and sensitivity, and increasing the speed of their electronic devices.

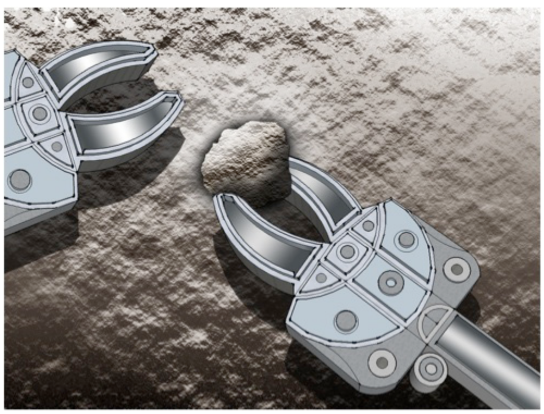


Figure 20. Teams of engineers compete in the Sample Return Robot challenge by designing and developing the next generation of autonomous robots to explore the landscapes of other worlds.

Source: NASA

Pillar 3: Expand understanding of the Earth and the universe (remote measurements)

Goal Summary

Remote measurements enable NASA to study many things in space: astronomical objects throughout the observable universe, planets throughout our galaxy, large and small celestial bodies in our solar system, and our own planet. Different types of technologies enable different kinds of remote measurements and different discoveries. In-space observatories, like the Hubble Space Telescope, have provided imaging of stellar events in distant galaxies, so NASA can learn more about the universe, how it works, and how it came to be. Other remote measurements are taken by robotic probes—autonomous scientific platforms, like the Cassini spacecraft, which orbits Saturn and reveals new information about the gas giant and its many distinctive moons. By investing in new remote measurement technologies, NASA will be able to answer some of humanity's greatest scientific questions and discover whole new mysteries about our solar system, our galaxy, and the universe.

Figure 21. Computer simulations derived from data from years of Hubble observations indicate the Andromeda and Milky Way galaxies will collide in 4 billion years, depicted in this artist's rendering.

Source: NASA

Capability Objectives

To achieve this goal, NASA will invest in technologies enabling four capability objectives:

- Achieve improved spacecraft system reliability and performance.
- Enable transportation to space.
- Enable space-based and Earth-based observation and analysis.
- Enable large-volume, efficient flight and ground computing and data management.

These capabilities will enable different kinds of remote measurements, such as those made with in-space and ground observatories and with robotic missions that can travel long distances while collecting, processing, analyzing, and transmitting data back to Earth.

GOAL 3

EXPAND UNDERSTANDING OF THE EARTH AND THE UNIVERSE (REMOTE MEASUREMENTS)

1. Achieve improved spacecraft system reliability and performance
    - Lightweight space structures and materials
    - Advanced power generation, storage, and transmission
    - High-bandwidth communications
2. Enable transportation to space
    - Launch propulsion systems
    - In-space propulsion
3. Enable space-based and earth-based observation and analysis
    - Scientific instruments and sensors
    - Design software
    - Structural monitoring
    - Cryogenic thermal management
4. Enable large-volume, efficient flight and ground computing and data management
    - Large-volume information processing
    - Improved flight computers
    - Modeling and simulation

Achieve Improved Spacecraft System Reliability and Performance

Missions conducting remote measurements in space require an integrated set of systems to operate reliably and perform efficiently. The spacecraft structure has to protect its many intricate systems and sensitive instruments as it travels in areas with extreme high and low temperatures, high radiation, and high potential for debris impacts. A constant supply of energy is required to power the various instruments and systems throughout the mission. Whether the mission remains in LEO or travels to the far reaches of the solar system, the data it collects will contribute to the search for new knowledge of the universe only if it can be transmitted back to Earth, where it can be studied by scientists.

New developments in these systems can enhance mission performance and enable new mission capabilities. Lightweight space structures and materials save mass for larger instruments without losing advantages in strength and durability. As with the previous two pillars, advanced power generation, storage, and transmission systems will be lighter and more efficient, so missions can travel farther and longer, to continuously observe space and space objects in new and enlightening ways. High-bandwidth communications will increase the speed, size, and quality of data transmissions, enabling constant data feeds for high-quality science.

Enable Transportation To Space

Some instruments for remote measurements remain close to Earth, like the Hubble Space Telescope stationed in LEO, and others are designed to travel far into space, like the Voyager spacecraft, which has traveled through the expanse of the solar system for over 30 years. All these instruments require launch propulsion systems to get to Earth orbit, and different missions will require different kinds of in-space propulsion to travel beyond Earth orbit.

Innovations in propulsion systems will enhance missions conducting remote measurements and enable new missions. Advanced launch propulsion systems must be able to carry more weight into space at a lower cost. This will allow for higher performing science missions, with larger, more sophisticated instruments and increased storage capacity for power systems or fuel. Innovations in in-space propulsion will enable missions of varying sizes and complexity to travel farther and faster than ever before.

Figure 22. The Solar Electric Propulsion project is developing in-space non-chemical propulsion systems to enable modern spacecraft to travel farther, faster, and cheaper than any other propulsion technology currently available.

Source: NASA

Enable Space-Based and Earth-Based Observation and Analysis

Innovations in instruments and software can enhance the quality and variety of remote measurements. Advanced scientific instruments and sensors can enable new science missions, like high-contrast exoplanet imaging and faint object spectroscopy over a broad spectral range. Other innovations could enhance Earth science missions, such as advanced lasers to obtain the Earth's 3D wind field and improve weather prediction capabilities. New science missions will depend on accurate design software to create complex instruments efficiently and affordably. Structural monitoring will help a mission retain high levels of performance, by detecting existing or potential faults in instruments and sensors, such as flaws in a mirror, and automatically preventing or self-correcting the fault. All in-space instruments and sensors require a cooling system to operate, and sensor performance often improves if the operating temperature is reduced. Cryogenic thermal management systems can provide reliable, long-life, vibration-free, and efficient cooling systems for a wide range of instruments, sensors, and associated electronics.

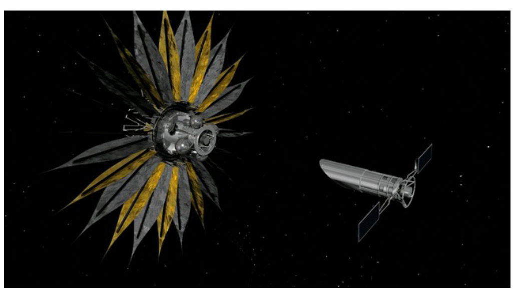


Figure 23. Artist's concept of a potential solution for imaging exoplanets: pairing a telescope with a starshade.

Source: NASA JPL

Enable Large-Volume, Efficient Flight and Ground Computing and Data Management

As remote measurements capture larger amounts of data and higher quality data, the demand for high-performance information processing systems becomes a greater challenge, both on the ground and in flight. Large-volume information processing will be necessary to process vast amounts of data to produce useful science. "Investments that address the challenges of…the fast-growing volume of large and complex collections of digital data…to advance agency missions and further scientific discovery and innovation" were also a priority in the Science and Technology Priorities for the FY 2014 Budget memorandum.

New flight computers must be ultra-reliable and radiation-hardened, enabling major performance improvements in onboard computing throughput, fault management, intelligent decision making, and science data acquisition. Developments in next generation space computing processors will optimize power usage and power efficiency for spaceflight computing. Other advancements should provide more flexible and less costly options for achieving fault-tolerant flight computing. Innovations in modeling and simulation will help analysts interpret and use complex data to predict space events and uncover other phenomena. Advancements in space-qualified computing hardware are necessary to meet the near- and long-term needs of NASA missions, especially for computing-intensive tasks in flight, such as autonomy; guidance, navigation, and control; and entry, descent, and landing.

Figure 24. The In-House Low Power Flight Computer for Cubesats project is one of NASA's current investments developing innovative flight and ground computing technologies.

Source: NASA

Innovations in data management will increase productivity of Heliophysics and Earth Science missions. For example, a 50 percent reduction in downlink data management planning for Mars Express could create increased robustness due to the ability to optimize and produce multi-day/week look-ahead plans. Adaptability in data management and analytic technologies could grow temporary storage requirements and online access to products for field campaigns. Innovative visualization and analysis of model outputs will enable new discoveries.

Pillar 4: Energize domestic space enterprise and extend benefits of space for the nation

Goal Summary

In addition to NASA, other U.S. entities—including Government agencies and an ever-expanding commercial space sector—play key roles in the advancement of space technology and contribute to U.S. leadership in space. By collaborating with these partners in space, NASA pursues an economical approach to space technology advancement and maximizes the benefits of space to the nation.

This goal is closely aligned with national goals and guidance. In accordance with the 2010 U.S. National Space Policy, this goal will ensure that NASA's technology investments are "encouraging and facilitating the growth of a U.S. commercial space sector that supports U.S. needs, is globally competitive, and advances U.S. leadership in the generation of new markets and innovation-driven entrepreneurship."[5] This goal will also fulfill direction from Congress in The National Aeronautics and Space Act, in which "Congress declares that the general welfare of the United States requires that the Administration seek and encourage, to the maximum extent possible, the fullest commercial use of space." Finally, this goal considers the NRC's recommendation on NASA Investments in Commercial Space Technology: "While OCT should focus primarily on developing advanced technologies of high value to NASA's own mission needs, OCT should also collaborate with the U.S. commercial space industry in the development of precompetitive technologies of interest to and sought by the commercial space industry." In response to this recommendation, NASA identified space technology investments that will benefit the commercial space sector and the nation.

Capability Objectives

While reviewing the Space Technology Roadmaps, the NRC considered how each technology area applied to national and commercial space needs. The NRC weighed this consideration in ranking each technology. In addition to this guidance from the NRC, the NASA SSTIP considers key technology priorities and related collaboration opportunities identified by other U.S. Government agencies and commercial space organizations. The result is a set of five capability objectives necessary to meet the goal of this pillar:

- Achieve improved spacecraft system reliability and performance.

- Enable transportation to and from space.
- Sustain human health and performance.
- Meet the robotic and autonomous navigation needs of space missions.
- Enable large-volume, efficient flight and ground computing and data management.

These objectives support both the needs of NASA and the broader space enterprise. Through partnership, resource collaboration, and direct technology infusion paths, U.S. space organizations can combine resources, achieve greater progress, and maximize the benefit of space technology investment to these players and the nation.

GOAL 4

ENERGIZE DOMESTIC SPACE ENTERPRISE AND EXTEND BENEFITS OF SPACE FOR THE NATION

1. Achieve improved spacecraft system reliability and performance
   - Lightweight space structures and materials
   - Increased available power
   - Autonomous rendezvous and dock
   - Vehicle safety
   - Earth observing
2. Enable transportation to and from space
   - Launch propulsion systems
   - In-space propulsion
   - EDL
   - Cryogenic storage and transfer
3. Sustain human health and performance
   - Space radiation mitigation
   - Long-duration ECLSS
   - Situational awareness and decision making
4. Meet the robotic and autonomous navigation needs of space missions
   - Robotic maneuvering
   - Autonomous rendezvous and dock
5. Enable large-volume, efficient flight and ground computing and data management
   - High data rates
   - Cybersecurity

Achieve Improved Spacecraft System Reliability and Performance

From space tourism to commercial satellites, reliable spacecraft and systems are essential to the emerging space industry. Current systems can be improved upon with innovations in the areas of lightweight space structures and materials, increased available power, autonomous rendezvous and docking, increased vehicle safety, and new Earth observing technologies. These innovations can dramatically increase the affordability, safety, and productivity of commercial, civil, and other Government space missions.

Innovations in lightweight structures and materials can greatly reduce the weight of launch vehicles and space structures, reducing the cost of both crewed and uncrewed launches. NASA's investment in lightweight structures and materials can also transition to ongoing commercial efforts developing inflatable space habitats.

All space missions can benefit from increased available power. Satellite developers, for example, want to increase power and energy storage in satellites to increase their communication capacity. Advancements in photovoltaic space power systems may be particularly beneficial, as all commercial communications satellites in geosynchronous Earth orbit rely exclusively on photovoltaic power systems.[6]

The first docking of a commercial vehicle to the ISS happened in May 2012, as part of the Commercial Orbital Transportation Services (COTS) agreement between commercial space company Space Exploration Technologies Corp. (SpaceX) and NASA. NASA investment in advanced autonomous rendezvous and docking systems can support similar, future collaborations with commercial space organizations, increasing the safety and reliability of docking activities—a major benefit to both parties.

Technologies for improving vehicle safety, such as integrated systems health management, fault detection and isolation and recovery (FDIR), and vehicle systems management, can significantly improve the robustness and reliability of both crewed and uncrewed space missions. These technologies can support commercial human spaceflight efforts, by diagnosing and potentially solving system failures or detecting events that require crew or passenger abort. By protecting spacecraft in flight, vehicle safety measures also have the potential to reduce space mission costs.

NASA investment in Earth observing technologies can benefit the many organizations already using such technologies, such as commercial imaging companies, the intelligence community, and some civil organizations, such as those monitoring climate and weather. In addition, space microwave, radar, or terahertz imaging systems can be applied to multiple Government and industrial applications. For example, Light Detection and Ranging (LIDAR) and Differential Absorption LIDAR remote sensing technologies have applications ranging from cloud diagnostics to smoke stack pollution compliance.[7]

Enable Transportation To and From Space

Commercial space companies face many of the same challenges as NASA when developing technologies for launch, transportation to orbit, in-space transportation, and return to Earth. Innovations in these technologies will improve the affordability and efficiency of transporting systems to, in, and from space.

The creation of more efficient and cost-effective launch propulsion systems can greatly impact the success and competitiveness of the commercial launch industry. In the NRC review panels, several commercial launch company representatives cited NASA investment in high-thrust hydrocarbon boost engines as a high priority, with potential benefits to small commercial launch systems or even a super heavy lift vehicle.[8]

Any organization that builds and uses satellites can benefit from more capable and efficient in-space propulsion. Today, low-power electric propulsion systems power the post-launch circularization of the orbits of large geosynchronous communications satellites and station-keeping for a wide range of spacecraft, including commercial communications satellites.[9] Higher efficiency electric propulsion and other advanced forms of in-space propulsion have the potential to greatly impact these and other commercial systems in space.

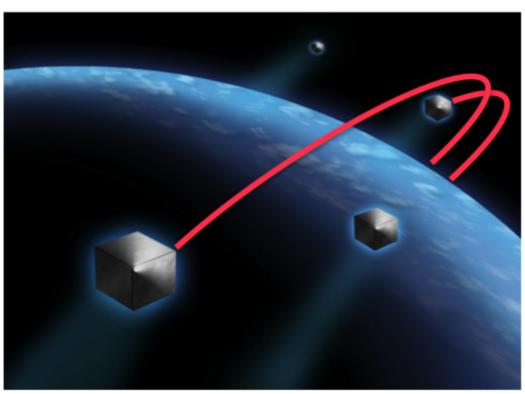


Figure 25. Teams compete in the Nano Satellite Launch Challenge to deliver a payload to Earth orbit, complete at least one orbit past the launch site, and deliver payloads successfully twice in one week.

Source: NASA

New EDL technologies can increase the safety and affordability of commercial space missions. EDL technologies are required for all commercial human spaceflight endeavors. Advancements in EDL can also significantly reduce mission costs for commercial launch companies, by enabling booster and cargo delivery vehicle recovery for reuse.

Lastly, as more commercial space companies plan future missions in LEO, they may benefit from the development of cryogenic storage and transfer technologies, enabling missions with higher performance, larger payloads, and longer range.

Sustain Human Health and Performance

Whether commercial space companies send humans to space for a few hours or for months, innovations in technologies to protect human health and sustain optimal performance will increase the safety and productivity of commercial space missions.

All space missions involving human crew or passengers will require technologies to protect humans from the effects of space radiation. There are no quantifiable limits to radiation impacts on the central nervous system, the cardiovascular system, and the immune system, and the established radiation exposure limits for professional astronauts are higher than for the general public.[10] Innovations in radiation risk modeling, prediction, and monitoring can help establish safe limits for commercial spaceflight passengers, or "space tourists." New countermeasures, such as advanced radiation shielding, may permit space tourists to safely spend more time in space, maybe even to orbit the Moon.

Commercial missions involving humans in space can also benefit from advancements in ECLSS technologies and technologies for situational awareness and decision-making. ECLSS technologies include air revitalization, water recovery, and waste management technologies The more reliable and resource-efficient an ECLSS is, the longer humans can live in space and the farther they can safely travel from Earth. Commercial human activities in space can be made safer and more reliable with advanced technologies for situational awareness and decision-making. For example, these technologies can help human crew or passengers predict and react to emergency situations, such as system failures or orbital debris impacts. Innovations in sustaining human health and performance also have the potential to benefit humans on Earth, through the development of new health and medical technologies that can transfer to commercial partners for terrestrial applications, such as water sanitation, telemedicine, and cancer treatments.

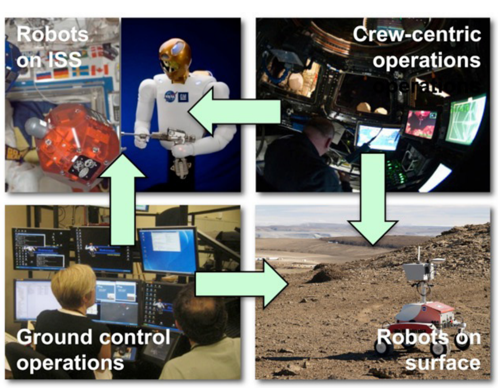


Figure 26. The Human Exploration Telerobotics project is a current NASA investment developing innovative robotic technologies.

Source: NASA

Meet the Robotic and Autonomous Navigation Needs of Space Missions

As commercial companies engage in more space activities, the need for advanced robotic and autonomous capabilities will increase. Advancements in technologies such as robotic maneuvering can enable such operations as on-orbit assembly of space structures, such as large satellites, cryogenic tanks, or space habitats. Robotic maneuvering may also be used for satellite servicing, to repair or extend the operational life of expensive commercial satellites or critical defense satellites. As discussed in the capability objective, Achieve Improved Spacecraft System Reliability and Performance, autonomous rendezvous and docking can increase the safety and reliability of any space mission in which a spacecraft docks to another, such as commercial cargo or crew delivery missions to the ISS.

Enable Large-Volume, Efficient Flight and Ground Computing and Data Management

From satellite operations to in-orbit crewed missions, the need for power-efficient, high-performance, radiation-tolerant computing systems is significant for civil, commercial, and other Government space activities. Technology advancements for providing high data rates can increase the efficiency of commercial satellites and enable remote sensing satellites with higher resolution imaging. Advancements in cybersecurity technology can protect the integrity of the massive amounts of data transmitted by communication satellites and are especially important for satellites with intelligence or defense purposes. Increasing cybersecurity measures also satisfies a national priority for science and technology development.[11]

Closing Thoughts – National Science and Technology Priorities

On June 6, 2012, the Office of Management and Budget and the Office of Science and Technology Policy released a memorandum to the heads of Executive Departments and Agencies in the United States. The four-page document detailed the White House's Science and Technology Priorities for the FY 2014 Budget. NASA's plan for strategic space technology investment, which began well before the release of this memorandum, addresses these critical science and technology priorities.

Research

Like the NASA SSTIP, the memorandum cites the importance of research: "Science and engineering research is a valuable source of new knowledge that has driven important developments in fields ranging from telecommunications to medicine, yielding high economic and social rates of return and creating entirely new industries with highly skilled, high-wage jobs." This motivation is similar to the NASA SSTIP's goal to invest in low-TRL technologies, which rely on research of a technology concept before development is possible. The memorandum also cites the importance of Government agencies partnering with commercial companies: "In particular, the nation benefits from government funding for basic and applied research in areas in which the private sector does not have the economic incentive to invest." By incorporating the priorities of NASA's commercial partners, the NASA SSTIP recognizes the benefit of NASA's investment in technology research and development to the private sector.

Prioritization

The memorandum's recommendation for prioritization is similar to the purpose of the NASA SSTIP: "In a time of constrained resources, agencies should continue to direct resources to high-priority activities and identify potential eliminations or reductions in less effective, lower quality, or lower priority programs." The NASA SSTIP is organized around such prioritization of activities, based on rigorous analysis of NASA's current technology investments and future plans. To ensure a comprehensive strategy for investment, NASA consulted with other Government agencies and commercial partners on their priorities for technology investment, just as the memorandum recommends: "Agencies engaged in complementary activities should consult with each other during the budget planning process so that resources are coordinated to maximize their impact and to avoid inappropriate duplication. They should also avoid duplicating research in areas that already receive funding from the private sector." By reaching out to other agencies and to its partners, NASA ensures its technology investments will be valuable to Federal and commercial organizations throughout the country.

Multi-Agency Priorities

The memorandum identified several areas as high priorities for multiple U.S. agencies, and every high priority is relevant to the NASA SSTIP. The Core technology investments Robotics and Autonomous Systems and Lightweight Space Structures and Materials can contribute to the development of the multi-agency priority of Advanced Manufacturing. NASA has developed many successful Clean Energy spinoffs with solar electric technologies and can continue to increase the power of these systems with investment in solar electric propulsion, part of the Core technology investment of Launch and In-Space Propulsion. The multi-agency priority of Global Climate Change is relevant to the Core technology investment of Space Radiation Mitigation and the Adjacent investment in Long-Duration Health Effects, both of which seek to better understand how extreme changes in an environment can affect human health. Like the Core technology investment ECLSS, the multi-agency priority of R&D for Informed Policy-Making and Management requires "development of sustainable food production systems that minimize the use of inputs such as water [and] energy." The multi-agency priority of Biological Innovation also relates to ECLSS. As mentioned earlier, the Adjacent technology investments of cybersecurity and nanotechnology both contribute to multi-agency priorities, namely Information Technology Research and Development and Nanotechnology. Lastly, the multi-agency priority of Innovation and Commercialization is a prevalent theme throughout the NASA SSTIP, particularly in the NASA SSTIP principles of investment.

Appendix A: Crosswalk of Investment Classifications to TABS

The NASA SSTIP investment approach and framework comprise space technology goals, capability objectives, technical challenges, and classifications of technology investments. A crosswalk of these results to both the Space Technology Roadmaps and the NRC's recommended top 16 near-term technology priorities is included in Tables 4 and 5, below.

Technology Investment Classification	Technology Investments	SSTIP Pillar 1	SSTIP Pillar 2	SSTIP Pillar 3	SSTIP Pillar 4	Associated NASA SSTIP Capability Objectives
Core	Launch and In-Space Propulsion	■	■	■	■	Enable transportation to, from, and on planetary bodies; Enable transportation to space; Enable transportation to and from space
Core	Robotics and Autonomous Systems	■	■	■	■	Achieve improved spacecraft system reliability and performance; Enable advanced in-situ measurement and exploration; Enable space-based and Earth-based observation and analysis; Meet the robotic and autonomous navigation needs of space missions
Core	High Data Rate Communications		■	■	■	Achieve improved spacecraft system reliability and performance; Enable large-volume, efficient flight and ground computing and data management
Core	Environmental Control and Life Support Systems	■			■	Achieve improved spacecraft system reliability and performance; Sustain human health and performance
Core	Space Radiation Mitigation	■			■	Sustain human health and performance
Core	Scientific Instruments and Sensors		■	■	■	Enable advanced in-situ measurement and exploration; Enable space-based and Earth-based observation and analysis; Achieve improved spacecraft system reliability and performance
Core	Entry, Descent, and Landing	■	■		■	Enable transportation to, from, and on planetary bodies; Enable transportation to and from space
Core	Lightweight Space Structures and Materials	■	■	■	■	Achieve improved spacecraft system reliability and performance; Enable space-based and Earth-based observation and analysis

Table 4. Crosswalk of Core investments, side A.

Associated NASA SSTIP Technical Challenge Areas	Related Level 2 TABS*	Associated NRC High Priorities (Top 16 in Bold)
Launch Propulsion Systems; High Power In-Space Propulsion; In-Space Propulsion; Cryogenic Storage and Transfer	1.1, 1.2, 1.3, 1.4, 2.1, 2.2, 2.4	**Electric Propulsion;** **(Nuclear) Thermal Propulsion;** Turbine Based Combined Cycle (TBCC); Rocket Based Combined Cycle (RBCC); Micro-Propulsion; Propellant Storage and Transfer
Autonomous Systems; Robotic Maneuvering, Manipulation, Sensing and Sampling; Autonomous Rendezvous and Docking; Structural Monitoring; Robotic Maneuvering	4.1, 4.2, 4.3, 4.4, 4.5, 4.6, 5.4 (5.4.3)	**Extreme Terrain Mobility;** **GNC (includes Relative Guidance Algorithms, Onboard Autonomous Navigation and Maneuvering);** Docking and Capture Mechanisms/Interfaces; Small Body/Microgravity Mobility; Dexterous Manipulation; Robotic Drilling and Sample Processing; Supervisory Control; Vehicle System Management and FDIR
High Bandwidth Communications; High Data Rates	5.1, 5.2, 5.5	Radio Systems
Long-Duration ECLSS	6.1	**ECLSS** **(includes: ECLSS Water Recovery and Management, Air Revitalization, ECLSS Waste Management, and Habitation)**
Space Radiation Mitigation	6.5	**Radiation Mitigation for Human Spaceflight (includes: Radiation Monitoring Technology, Radiation Protection Systems, Radiation Risk Assessment Modeling, Radiation Prediction, and Radiation Mitigation)**
Life Detection; Advanced Sensors (all types of detecting sensors: geological, chemical, etc.); Scientific Instruments and Sensors; Earth Observing	8.1, 8.2, 8.3	**Detectors and Focal Planes;** **Optical Systems (Instruments and Sensors);** **High Contrast Imaging and Spectroscopy Technologies;** **In-Situ Instruments and Sensors;** Electronics for Instruments and Sensors; Laser for Instruments and Sensors; Wireless Spacecraft Technology
Advanced Entry, Descent, and Landing; Entry, Descent, and Landing	9.1, 9.2, 9.3, 9.4, 14.3	**EDL TPS (includes Rigid TPS, Flexible TPS, and Ascent/Entry TPS);** **GNC (includes GNC Sensors and Systems [EDL]);** EDL Instrumentation and Health Monitoring; EDL Modeling and Simulation; EDL System Integration and Analysis; Atmospheric and Surface Characterization; Deployable Hypersonic Decelerators
Lightweight Space Structures and Materials; Structural Monitoring	10.1 (10.1.1), 12.1, 12.2	**Lightweight and Multifunctional Materials and Structures (includes: [Nano] Lightweight Materials and Structures; Structures: Innovative, Multifunctional Concepts; Structures: Lightweight Concepts; Materials: Lightweight Structure; and Structures: Design and Certification Methods)**

*To download the Space Technology Roadmaps and TABS sequence, visit http://www.nasa.gov/offices/oct/home/roadmaps/index.html

Table 4. Crosswalk of Core investments, side B.

Technology Investment Classification	Technology Investments	SSTIP Pillar 1	SSTIP Pillar 2	SSTIP Pillar 3	SSTIP Pillar 4	Associated NASA SSTIP Capability Objectives
Adjacent	Power Generation	■	■	■	■	Achieve improved spacecraft system reliability and performance
Adjacent	Energy Storage	■	■	■	■	Achieve improved spacecraft system reliability and performance
Adjacent	Power Management and Distribution	■	■	■	■	Achieve improved spacecraft system reliability and performance
Adjacent	Internetworking					
Adjacent	Position, Navigation, and Timing		■			Enable transportation to, from, and on planetary bodies
Adjacent	Extravehicular Activity Systems	■				Enable payload delivery and human exploration of destinations and planetary bodies
Adjacent	Long-Duration Crew Health	■				Sustain human health and performance
Adjacent	Safety and Emergency Response					
Adjacent	In-Situ Resource Utilization					Enable payload delivery and human exploration of destinations and planetary bodies
Adjacent	Sustainability and Supportability	■				Enable payload delivery and human exploration of destinations and planetary bodies
Adjacent	Surface Mobility	■				Enable payload delivery and human exploration of destinations and planetary bodies
Adjacent	Advanced Habitat Systems	■				Enable payload delivery and human exploration of destinations and planetary bodies
Adjacent	Crosscutting Destination Systems	■				Enable payload delivery and human exploration of destinations and planetary bodies
Adjacent	Nanotechnology: Energy Generation and Storage		■			Enable advanced in-situ measurement and exploration
Adjacent	Nanotechnology: Propulsion		■			Enable advanced in-situ measurement and exploration
Adjacent	Nanotechnology: Sensors, Electronics, and Devices		■			Enable advanced in-situ measurement and exploration
Adjacent	Computing			■		Enable large-volume, efficient flight and ground computing and data management
Adjacent	Modeling			■		Enable large-volume, efficient flight and ground computing and data management
Adjacent	Simulation			■		Enable large-volume, efficient flight and ground computing and data management
Adjacent	Mechanical Systems					
Adjacent	Manufacturing					
Adjacent	Crosscutting Materials, Structures, and Mechanisms					
Adjacent	Active Thermal Control of Cryogenic Systems					Enable space-based and Earth-based observation and analysis

Table 5. Crosswalk of Adjacent investments, side A.

Associated NASA SSTIP Technical Challenge Areas	Related Level 2 TABS	Associated NRC High Priorities (Top 16 in Bold)
Advanced Power Generation, Storage, and Transmission; Increased Available Power	3.1	**Solar Power Generation (Photovoltaic and Thermal);** **Fission Power Generation;** Radioisotope Power Generation
Advanced Power Generation, Storage, and Transmission; Increased Available Power	3.2	Batteries
Advanced Power Generation, Storage, and Transmission; Increased Available Power	3.3	Power Distribution and Transmission; Power Conversion and Regulation
	5.3	Adaptive Network Topology
Efficient Accurate Navigation, Positioning, and Timing	5.4 (except 5.4.3)	Timekeeping and Time Distribution
EVA	6.2	Extravehicular Activity Portable Life Support System; Extravehicular Activity Pressure Garment
Long-Duration Health Effects	6.3	**Long-Duration Crew Health**
	6.4	Fire Detection and Suppression; Fire Remediation
Surface Systems	7.1 (7.1.2, 7.1.3, 7.1.4)	ISRU Resource Acquisition; ISRU Products/Production; ISRU Manufacturing/Infrastructure, etc.
Surface Systems	7.2	Food Production, Processing, and Preservation; Autonomous Logistics Management; Maintenance Systems
Surface Systems	7.3	Surface Mobility
Surface Systems	7.4	Smart Habitats; Habitation Evolution
Surface Systems	7.6	Construction and Assembly; Dust Prevention and Mitigation
Nanotechnology	10.2	Energy Generation (Nano)
Nanotechnology	10.3	Nanopropellants
Nanotechnology	10.4	Sensors and Actuators (Nano)
Improved Flight Computers	11.1	Flight Computing; Ground Computing
Modeling and Simulation	11.2	Science Modeling and Simulation
Modeling and Simulation	11.3	Distributed Simulation
	12.3 (12.3.1, 12.3.4, 12.3.5)	Deployables, Docking, and Interfaces; Mechanisms: Design and Analysis Tools and Methods; Mechanisms: Reliability/Life Assessment/Health Monitoring
	12.4 (12.4.2)	Intelligent Integrated Manufacturing and Cyber Physical Systems
	12.5 (12.5.1)	Nondestructive Evaluation and Sensors
Cryogenic Thermal Management	14.1, 14.2	**Active Thermal Control of Cryogenic Systems**

Table 5. Crosswalk of Adjacent investments, side B.

Appendix B: Summary of 2012 Investments

This section summarizes NASA's pioneering and crosscutting technology investments in FY 2012 and how they align with recommendations made by the NRC and in this NASA SSTIP. For up-to-date information on NASA's technology development programs and projects, visit the OCT website and TechPort. Table 6 includes a full list of NASA's current space technology programs, by Mission Directorate and Office.

Science Mission Directorate	**Office of the Chief Technologist**
Astrophysics Research and Analysis	Centennial Challenges
Discovery Program (502A)	Center Innovation Fund
ESTO	Flight Opportunities
Exoplanet Exploration	Franklin Small Satellite Subsystems Technologies
HELIOS	Game Changing Development
Mars Exploration (269B)	NASA Innovative Advanced Concepts
NASA Earth Sciences	SBIR
Physics of the Cosmos (PCOS)	Small Spacecraft Technology Program
Planetary Science Research (515A)	Space Technology Research Grants, Space Technology Research Fellowships
Technology Program (051A)	STTR
Human Exploration and Operations Mission Directorate (HEOMD)	Technology Demonstration Missions
Advanced Exploration Systems	**Office of Safety and Mission Assurance (OSMA)**
SCaN	NASA Electronic Parts and Packaging Program
Robotic Servicing	Nondestructive Evaluation Program
Center Internal Research and Development (IRAD)	OSMA Software Assurance Research Program (SARP)
GSFC IRAD	Range Safety
JSC IRAD	**Office of the Chief Information Officer (OCIO)**
KSC IRAD	Chief Information Officer

Table 6. FY 2012 space technology programs by Mission Directorate and Office.

Pioneering and crosscutting technology investments provide capabilities fundamental to the Agency's direction and the U.S. space enterprise to increase the affordability, safety, and feasibility of missions and ultimately enable travel to and exploration of destinations never before visited. Mission-specific technology investments provide particular capabilities identified for funded or planned missions. These investments are more narrowly focused and nearer term than pioneering and crosscutting investments.

During FY 2012, NASA manages 1,237 pioneering and crosscutting investment projects divided among six responsible Offices and Mission Directorates. The total pioneering and crosscutting investment across the Agency is nearly $1 billion. About 90 percent of these investments (over 1,100 projects) represent investments of less than $500K per project. These investments are managed by OCT-STP, the Office of Safety and Mission Assurance (OSMA), Centers (Center IRAD), the Office of the Chief Information Officer (OCIO), SMD, and HEOMD. OCT-STP is responsible for the largest number of these investments, with over 900 projects, 95 percent of which are investments of less than $500K.

Analysis of these 1,237 projects shows that 40 percent of NASA's pioneering and crosscutting investments are among the NRC's top 16 technology priorities (shown in Figure 27). The NRC also recommended that at least 10 percent of the Agency investment be in low-TRL (TRLs 1 and 2) technologies. Figure 28 shows that 18

Figure 27. Percent of pioneering and crosscutting Agency investment in NRC top 16 priorities.

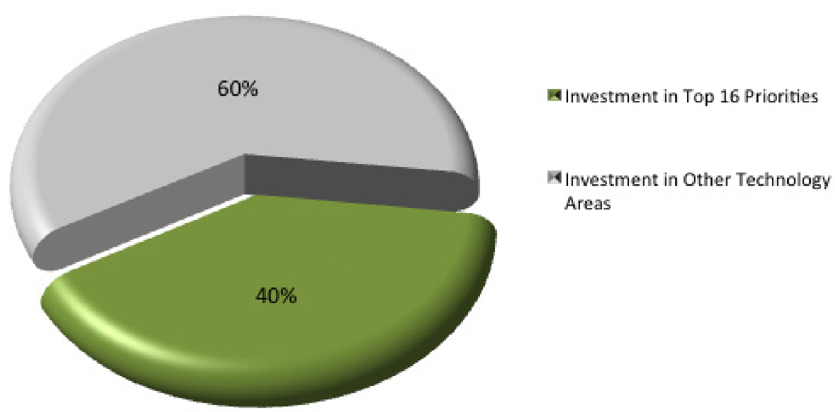
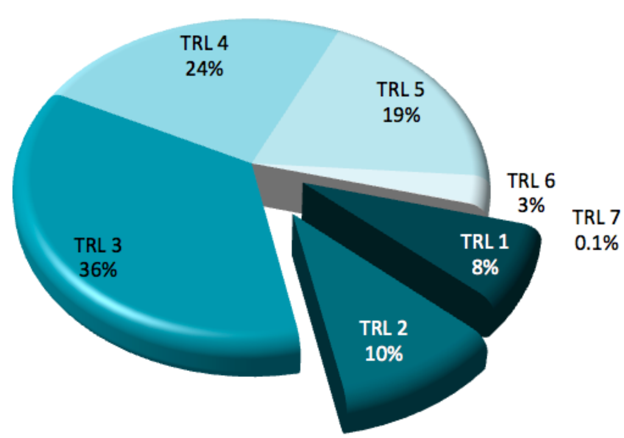


Figure 28. Pioneering and crosscutting Agency investment by TRL.



percent of the FY 2012 investment is currently in low-TRL projects. The majority of pioneering and crosscutting technology investment is in medium-TRL (3, 4, and 5) technology development projects.

Figure 29 shows FY 2012 pioneering and crosscutting technology investments in each of the NRC top 16 priorities. This chart shows that the majority of investments in the NRC top 16 priorities are in the ECLSS, GNC, and EDL TPS priorities. Within ECLSS, some of the largest investments include the AES program's Atmosphere Resource Recovery & Environmental Monitoring for Long Duration Exploration, Habitat Systems, Logistics Reduction and Repurposing, and Water Recovery projects. Other large investments in this priority include the STP Next Generation Life Support, Space Synthetic Biology, and a portion of the Autonomous Systems project. The largest portion of the GNC investments is the AES program's Morpheus VTB/ALHAT project. The EDL TPS investments are largely comprised of the STP Technology Demonstration Mission Low Density Supersonic Decelerators project.

The priorities with lowest FY 2012 pioneering and crosscutting investment include Fission Power Generation, Long-Duration Crew Health, Detectors and Focal Planes, and Active Thermal Control of Cryogenic Systems. These are potential gap areas for further investment.

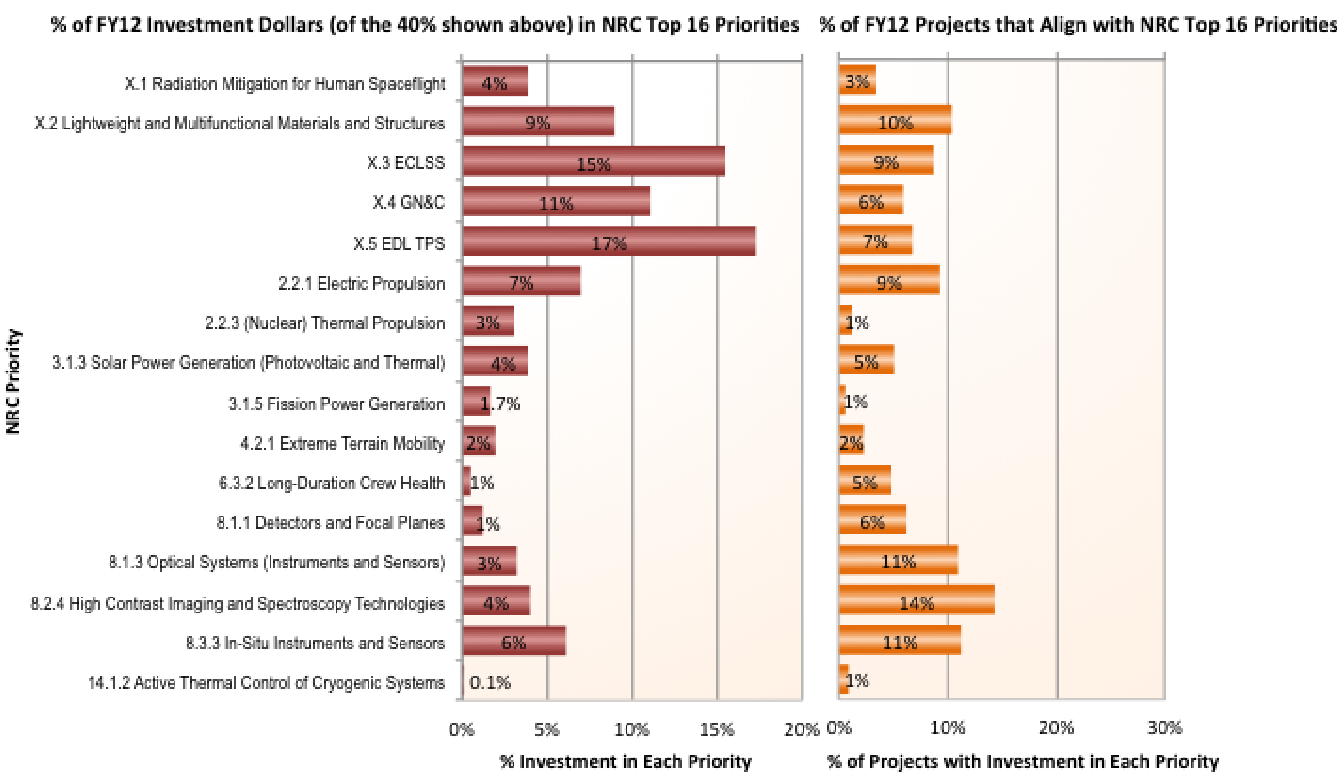


Figure 29. FY 2012 investment in NRC top 16 priorities and number of FY 2012 projects aligned with NRC top 16 priorities.

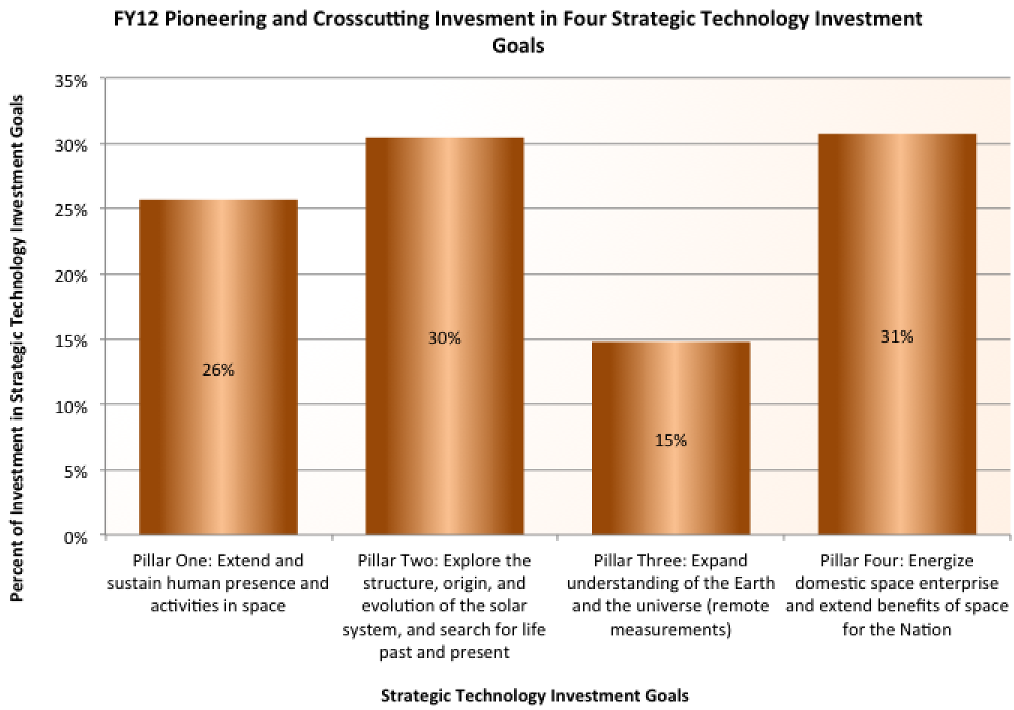


Figure 30. FY 2012 investment in four strategic technology investment goals.

Figure 30 shows how FY 2012 pioneering and crosscutting investments align to each of the four pillars of the NASA SSTIP framework. Investment in each pillar represents the total investment in projects aligned to that goal; projects may be aligned with more than one goal. This figure shows there are no gaps in investment among the four goals. The greatest investment is fairly even across goals 1, 2, and 4, and goal 3 has the least investment.

Additional analysis of the FY 2012 pioneering and crosscutting investments against NASA SSTIP technology investment classifications shows 71 percent of investments in Core, 20 percent in Adjacent, and 9 percent in Complementary. These results are consistent with the NASA SSTIP approach, which specifies 70 percent of investment in Core, 20 percent investment in Adjacent, and 10 percent of investment in Complementary technology investments.

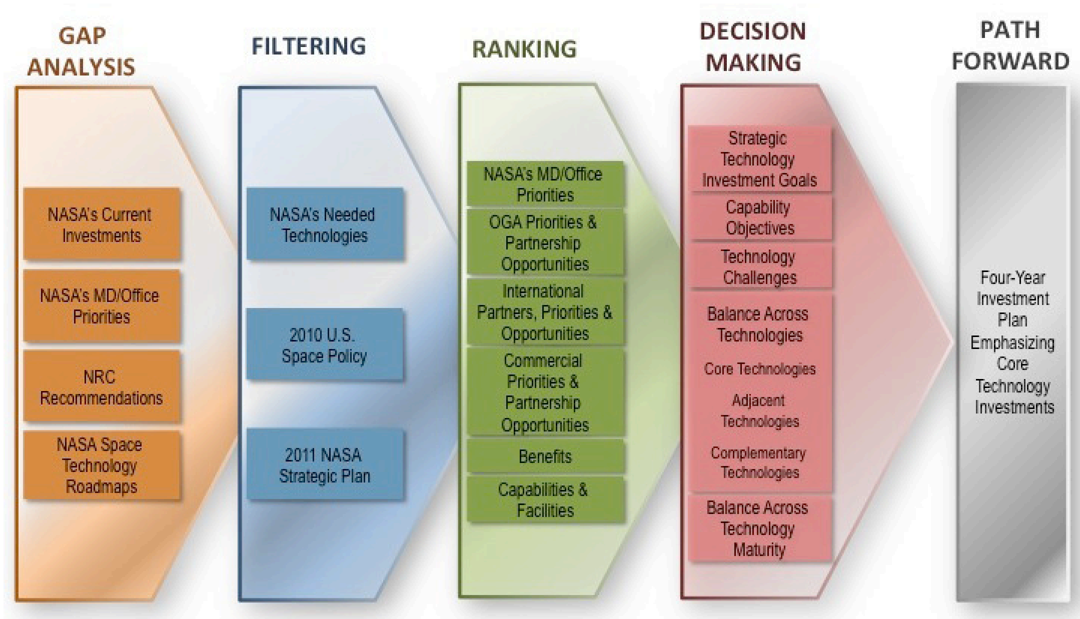
Appendix C: Summary of the NASA SSTIP Development Process

The NASA SSTIP development process included four major steps (Figure 31):

1) Gap analysis
2) Filtering
3) Ranking
4) Decision making

To complete these steps, OCT collected NASA's current pioneering and crosscutting technology investments, analyzed them against priorities, identified technology gaps where high priorities were unfunded, verified these priorities were consistent with NASA's strategy and U.S. policy, and ranked the priorities to determine the Agency's highest priority space technology investment needs. These high-priority needs were evaluated by NASA's senior leaders at decision-making meetings to create the NASA SSTIP. The senior leaders carefully evaluated the priorities to determine the content of the plan, ensuring that it provides a balanced and effective approach. In this context, the leadership team did not interpret balance to mean equal amounts of investment. Rather, they used the term balance to refer to traceable prioritization of investment across

Figure 31. FY 2012 investment in four strategic technology investment goals.



all 14 technical areas in the Space Technology Roadmaps, at each TRL, and in both mission-focused, or "pull," technologies and pioneering and crosscutting "push" technologies. The senior leaders developed the NASA SSTIP framework, investment approach, and defined the governance for its execution. This process is further described below.

Gap Analysis

NASA collected data from five major sources to conduct the gap analysis:

- NASA Space Technology Roadmaps.
- NRC recommendations as documented in *NASA Space Technology Roadmaps and Priorities: Restoring NASA's Technological Edge and Paving the Way for a New Era in Space* (2012).
- Mission Directorate priorities.
- NASA's current space technology investments from 1,237 active NASA projects.
- Priorities of other Government agencies, international partners, and commercial sector entities, in response to a data call by OCT.

Space Technology Roadmaps and Technology Area Breakdown Structure

The Space Technology Roadmaps were developed to support NASA's technology prioritization and planning activities. These roadmaps include detailed technology milestones that represent major technology investments in 320 technologies over the next 20 years. For the NASA SSTIP, NASA extracted near-term milestones from the roadmaps, resulting in potential technology development activities over the next four years, through 2016. These technology development activities are structured by the Technology Area Breakdown Structure (TABS); account for time sequencing and interdependencies; and represent potential technologies that will enable near-term successes, continued technology maturation and demonstration, and long-term goal achievement.

Figure 32. NASA SSTIP development process by sources.

NRC Priorities and Recommendations

The NRC conducted an independent evaluation of the Space Technology Roadmaps and developed a set of technology priorities and technology investment recommendations for NASA. The NRC developed three technology objectives, 100 top technical challenges, and 83 high-priority technologies from the technologies described in the roadmaps. Of those 83 high-priority technologies, 16 were identified as top priorities for near-term investment by NASA, based on their close ties to the Agency's primary exploration and science objectives and related technical challenges.

With the prioritized technologies identified in the report, the NRC also provided specific technology investment recommendations, including:

- Providing a process to manage the investment and progression of technologies from development to use.
- Investing in tipping point technologies that could yield large advances with relatively small investments.
- Sustaining a modest investment in low-TRL technology.
- Enabling flight demonstrations for high-TRL technologies in collaboration with NASA and outside partners.

Data Call on Current Investments

To support the NASA SSTIP process, OCT issued an Agency-wide data call to capture all pioneering and crosscutting space technology investment areas from across NASA. In just three weeks, NASA's Mission Directorates and Offices responded positively to the data call, providing detailed technology data on 1,237 technology projects. A large amount of data was collected for each technology project, including project descriptions, technology readiness levels, technology areas, responsible parties, and partnerships. The inventory includes technology projects from OCT-STP, HEOMD, SMD, OSMA, the Center IRAD programs, and OCIO. Because the Aeronautics Research Mission Directorate operates with a previously approved National Aeronautics Research and Development plan, their projects were not included in the NASA SSTIP or the project inventory. At the time of the data call, some programs within Mission Directorates and Offices had not completed the FY 2012 technology solicitation, selection, and awards process. Known solicitations were added to this analysis (included in the 1,237 technology projects) using the topic areas, technology readiness level requested, and solicited project values.

Priorities of Internal and External Stakeholders

OCT sought input from NASA's internal stakeholders—Mission Directorates and Offices—and external stakeholders and partners—other Government agencies, commercial space entities, and international partners—on their top priorities for space technology investment. Each Mission Directorate and Office used its own internal process to identify technical challenges, needed capabilities, and priorities. For example, HEOMD leveraged previous work completed by the

Human Space Flight Architecture Team to develop its priorities. The priorities of Mission Directorates and Offices represent an internal perspective of the top needs across all of NASA's missions in human spaceflight, science, and space technology. When OCT received responses from other Government agencies, international partners, and commercial space entities, their lists of technology investment priorities were compared to the NRC's and internal priorities to determine a comprehensive list of crosscutting technologies that could provide the most significant benefit to the nation.

Analysis

OCT used a rigorous process to organize and link current project data through the Space Technology Roadmap TABS. Then, analysts compared the current NASA space technology investments against the NRC recommendations to identify gaps in technology investments. Similarly, the analysts compared the current NASA space technology investments against the comprehensive list of internal and external stakeholders' technology investment priorities and identified gaps. These technology gaps were evaluated against the NASA Space Technology Roadmaps to verify that all critical technology needs had been captured. The gap analysis resulted in a detailed list of NASA technology investments, a compiled list of high-priority technology themes, and an understanding of unfunded priorities.

Filtering

Beginning with the products of the gap analysis, NASA analysts compared the list of high-priority themes with the 2010 U.S. Space Policy, 2011 NASA Strategic Plan, and individual Mission Directorate inputs. The purpose of this step is to verify that all technologies on the new, refined list met national policy, the NASA Strategic Plan, and Mission Directorate needs. The list is complete, but a few minor discrepancies received additional evaluation in the fourth step of the process, described below.

Ranking

The consolidated list of high-priority technology themes is long enough that the NASA SSTIP further distinguishes among these high priorities: it establishes a more limited list that may be achieved within the anticipated technology budget for space technology across the Agency in FY 2013 to FY 2016, the timeframe that the present release of the NASA SSTIP covers. At the time of this writing, this total includes the budget for mission-specific technology investments and pioneering and crosscutting work. Specifically, it includes the Space Technology Program and certain work within technology programs managed by NASA Mission Directorates and Offices, such as the AES program. The total for pioneering and crosscutting technologies is approximately $1 billion per year. The total for mission-specific technology investments varies with the year-to-year expenditures associated with specific missions.

The ranking captured the priorities of NASA's external stakeholders, including other Government agencies, international partners, and the commercial sector. This approach enables appropriate consideration of potential collaborative activities. If there is something in it for NASA—more than what could be achieved without a partnership—such an opportunity can be given greater weight in deciding the makeup of NASA's technology portfolio.

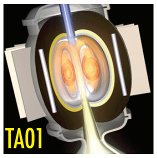
Rankings were based on several criteria, including NASA Mission Directorate priorities met; NRC priorities met; crosscutting capabilities provided to NASA, other Government agencies, international partners, and the space industry; partnership opportunities; current investment; available facilities and workforce; and overall benefits provided to NASA and the nation. The product of this step is a ranked list of needed technologies.

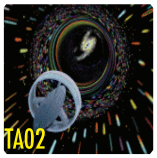
Decision Making

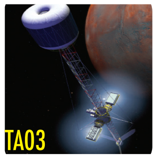
NASA senior leaders, including representation from each Mission Directorate, collaborated in a series of Agency meetings to develop a balanced portfolio considering the ranked list of NASA and stakeholder priorities, the Agency-level budget, progress in currently funded technologies, and NRC guidance to provide balance across technology areas and TRL range. This activity resulted in the NASA SSTIP's investment approach and framework. The senior leadership decided on a 70-20-10 approach for balancing investment—70 percent of technology investment in mission-specific and eight Core pioneering and crosscutting technologies, 20 percent in Adjacent pioneering and crosscutting technologies, and 10 percent in Complementary pioneering and crosscutting technologies. They also developed the four pillars of Agency investment that provide the framework for NASA's space technology investment strategy. The senior leaders collaboratively arrived at these conclusions, as well as the appropriate principles to balance the portfolio and execute the plan. Lastly, the meetings determined that NTEC would be the governing body of the report. NTEC reviewed this NASA SSTIP and will review and lead decisions guiding future editions of the NASA SSTIP.

Appendix D: Updated Space Technology Roadmap TABS

The 14 Technology Area teams considered the NRC's recommendations for revising the Space Technology Roadmap Areas and made changes accordingly. The final Space Technology Roadmap TABS is included below, in a two-page spread.







TA01 • LAUNCH PROPULSION SYSTEMS

Solid Rocket Propulsion Systems
- Propellants
- Case Materials
- Nozzle Systems
- Hybrid Rocket Propulsion Systems
- Fundamental Solid Propulsion Technologies

Liquid Rocket Propulsion Systems
- LH_2/LOX Based
- RP/LOX Based
- CH_4/LOX Based
- Detonation Wave Engines (Closed Cycle)
- Propellants
- Fundamental Liquid Propulsion Technologies

Air Breathing Propulsion Systems
- TBCC
- RBCC
- Detonation Wave Engines (Open Cycle)
- Turbine Based Jet Engines (Flyback Boosters)
- Ramjet/Scramjet Engines (Accelerators)
- Deeply-cooled Air Cycles
- Air Collection & Enrichment System
- Fundamental Air Breathing Propulsion Technologies

Ancillary Propulsion Systems
- Auxiliary Control Systems
- Main Propulsion Systems (Excluding Engines)
- Launch Abort Systems
- Thrust Vector Control Systems
- Health Management & Sensors
- Pyro & Separation Systems
- Fundamental Ancillary Propulsion Technologies

Unconventional / Other Propulsion Systems
- Ground Launch Assist
- Air Launch / Drop Systems
- Space Tether Assist
- Beamed Energy / Energy Addition
- Nuclear
- High Energy Density Materials/Propellants

TA02 • IN-SPACE PROPULSION TECHNOLOGIES

Chemical Propulsion
- Liquid Storable
- Liquid Cryogenic
- Gels
- Solid
- Hybrid
- Cold Gas/Warm Gas
- Micro-propulsion

Non-Chemical Propulsion
- Electric Propulsion
- Solar Sail Propulsion
- Thermal Propulsion
- Tether Propulsion

Advanced (TRL <3) Propulsion Technologies
- Beamed Energy Propulsion
- Electric Sail Propulsion
- Fusion Propulsion
- High Energy Density Materials
- Antimatter Propulsion
- Advanced Fission
- Breakthrough Propulsion

Supporting Technologies
- Propellant Storage & Transfer

TA03 • SPACE POWER & ENERGY STORAGE

Power Generation
- Energy Harvesting
- Chemical (Fuel Cells, Heat Engines)
- Solar (Photo-Voltaic & Thermal)
- Radioisotope
- Fission
- Fusion

Energy Storage
- Batteries
- Flywheels
- Regenerative Fuel Cells

Power Management & Distribution
- FDIR
- Management & Control
- Distribution & Transmission
- Wireless Power Transmission
- Conversion & Regulation

Cross Cutting Technology
- Analytical Tools
- Green Energy Impact
- Multi-functional Structures
- Alternative Fuels

TA04 • ROBOTICS, TELE-ROBOTICS & AUTONOMOUS SYSTEMS

Sensing & Perception
- 3-D Perception
- Relative Position & Velocity Estimation
- Terrain Mapping, Classification & Characterization
- Natural & Man-made Object Recognition
- Sensor Fusion for Sampling & Manipulation
- Onboard Science Data Analysis

Mobility
- Extreme Terrain Mobility
- Below-Surface Mobility
- Above-Surface Mobility
- Small Body/Microgravity Mobility

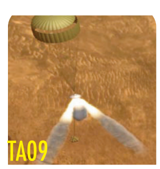
Manipulation
- Robot Arms
- Dexterous Manipulators
- Modeling of Contact Dynamics
- Mobile Manipulation
- Collaborative Manipulation
- Robotic Drilling & Sample Processing

Human-Systems Integration
- Multi-Modal Human-Systems Interaction
- Supervisory Control
- Robot-to-Suit Interfaces
- Intent Recognition & Reaction
- Distributed Collaboration
- Common Human-Systems Interfaces
- Safety, Trust, & Interfacing of Robotic/Human Proximity Operations

Autonomy
- Vehicle Systems Management & FDIR
- Dynamic Planning & Sequencing Tools
- Autonomous Guidance & Control
- Multi-Agent Coordination
- Adjustable Autonomy
- Terrain Relative Navigation
- Path & Motion Planning with Uncertainty

Auton. Rendezvous & Docking
- Relative Navigation Sensors (long-, mid-, near-range)
- Guidance Algorithms
- Docking & Capture Mechanisms/ Interfaces
- Mission/System Managers for Autonomy/Automation

RTA Systems Engineering
- Modularity/Commonality
- Verification & Validation of Complex Adaptive Systems
- Onboard Computing



TA05 • COMMUNICATION & NAVIGATION

Optical Comm. & Navigation
- Detector Development
- Large Apertures
- Lasers
- Acquisition & Tracking
- Atmospheric Mitigation

Radio Frequency Communications
- Spectrum Efficient Technologies
- Power Efficient Technologies
- Propagation
- Flight & Ground Systems
- Earth Launch & Reentry Comm.
- Antennas

Internetworking
- Disruptive Tolerant Networking
- Adaptive Network Topology
- Information Assurance
- Integrated Network Management

Position, Navigation, and Timing
- Timekeeping & Time Distribution
- Onboard Auto Navigation & Maneuver
- Sensors & Vision Processing Systems
- Relative & Proximity Navigation
- Auto Precision Formation Flying
- Auto Approach & Landing

Integrated Technologies
- Radio Systems
- Ultra Wideband
- Cognitive Networks
- Science from the Comm. System
- Hybrid Optical Comm. & Nav. Sensors
- RF/Optical Hybrid Technology

Revolutionary Concepts
- X-Ray Navigation
- X-Ray Communications
- Neutrino-Based Navigation & Tracking
- Quantum Key Distribution
- Quantum Communications
- SQIF Microwave Amplifier
- Reconfigurable Large Apertures Using Nanosat Constellations

TA06 • HUMAN HEALTH, LIFE SUPPORT & HABITATION SYSTEMS

Environmental Control & Life Support Systems & Habitation Sys.
- Air Revitalization
- Water Recovery & Management
- Waste Management
- Habitation

Extravehicular Activity Systems
- Pressure Garment
- Portable Life Support System
- Power, Avionics & Software

Human Health & Performance
- Medical Diagnosis / Prognosis
- Long-Duration Health
- Behavioral Health
- Human Factors

Environmental Monitoring, Safety & Emergency Response
- Sensors: Air, Water, Microbial, etc.
- Fire: Detection, Suppression, Recovery
- Protective Clothing / Breathing
- Remediation

Radiation
- Risk Assessment Modeling
- Radiation Mitigation
- Protection Systems
- Radiation prediction
- Monitoring Technology

TA07 • HUMAN EXPLORATION DESTINATION SYSTEMS

In-Situ Resource Utilization
- Destination Reconnaissance, Prospecting, & Mapping
- Resource Acquisition
- Consumables Production
- Manufacturing Products & Infrastructure Emplacement

Sustainability & Supportability
- Autonomous Logistics Management
- Maintenance Systems
- Repair Systems
- Food Production, Processing, & Preservation

"Advanced" Human Mobility Systems
- EVA Mobility
- Surface Mobility
- Off-Surface Mobility

"Advanced" Habitat Systems
- Integrated Habitat Systems
- Habitat Evolution
- "Smart" Habitats
- Artificial Gravity

Mission Operations & Safety
- Crew Training
- Planetary Safety
- Integrated Flight Operations Systems
- Integrated Risk Assessment Tools

Cross-Cutting Systems
- Construction & Assembly
- Particulate Contamination Prevention & Mitigation

TA08 • SCIENCE INSTRUMENTS, OBSERVATORIES & SENSOR SYSTEMS

Remote Sensing Instruments / Sensors
- Detectors & Focal Planes
- Electronics
- Optical Components
- Microwave / Radio
- Lasers
- Cryogenic / Thermal

Observatories
- Mirror Systems
- Structures & Antennas
- Distributed Aperture

In-Situ Instruments / Sensor
- Particles: Charged & Neutral
- Fields & Waves
- In-Situ

TA09 • ENTRY, DESCENT & LANDING SYSTEMS

Aeroassist & Atmospheric Entry
- Rigid Thermal Protection Systems
- Flexible Thermal Protection Systems
- Rigid Hypersonic Decelerators
- Deployable Hypersonic Decelerators

Descent
- Attached Deployable Decelerators
- Trailing Deployable Decelerators
- Supersonic Retropropulsion

Landing
- Touchdown Systems
- Egress & Deployment Systems
- Propulsion Systems
- Small Body Systems

Vehicle Systems Technology
- Separation Systems
- System Integration and Analyses
- Atmosphere & surface characterization
- Modeling and Simulation
- Instrumentation and Health Monitoring
- GN&C Sensors and Systems

TA10 • NANOTECHNOLOGY

Engineered Materials & Structures
- Lightweight Structures
- Damage Tolerant Systems
- Coatings
- Adhesives
- Thermal Protection & Control

Energy Generation & Storage
- Energy Storage
- Energy Generation

Propulsion
- Propellants
- Propulsion Components
- In-Space Propulsion

Sensors, Electronics & Devices
- Sensors & Actuators
- Nanoelectronics
- Miniature Instruments

TA11 • MODELING, SIMULATION, INFORMATION TECHNOLOGY & PROCESSING

Computing
- Flight Computing
- Ground Computing

Modeling
- Software Modeling & Model-Checking
- Integrated Hardware & Software Modeling
- Human-System Performance Modeling
- Science Modeling
- Frameworks, Languages, Tools & Standards

Simulation
- Distributed Simulation
- Integrated System Lifecycle Simulation
- Simulation-Based Systems Engineering
- Simulation-Based Training & Decision Support Systems

Information Processing
- Science, Engineering & Mission Data Lifecycle
- Intelligent Data Understanding
- Semantic Technologies
- Collaborative Science & Engineering
- Advanced Mission Systems

TA12 • MATERIALS, STRUCTURES, MECHANICAL SYSTEMS & MANUFACTURING

Materials
- Lightweight Structure
- Computational Design
- Flexible Material Systems
- Environment
- Special Materials

Structures
- Lightweight Concepts
- Design & Certification Methods
- Reliability & Sustainment
- Test Tools & Methods
- Innovative, Multifunctional Concepts

Mechanical Systems
- Deployables, Docking and Interfaces
- Mechanism Life Extension Systems
- Electro-mechanical, Mechanical & Micromechanisms
- Design & Analysis Tools and Methods
- Reliability / Life Assessment / Health Monitoring
- Certification Methods

Manufacturing
- Manufacturing Processes
- Intelligent Integrated Manufacturing and Cyber Physical Systems
- Electronics & Optics Manufacturing Process
- Sustainable Manufacturing

Cross-Cutting
- Nondestructive Evaluation
- Model-Based Certification & Sustainment Methods
- Loads and Environments

TA13 • GROUND & LAUNCH SYSTEMS PROCESSING

Technologies to Optimize the Operational Life-Cycle
- Storage, Distribution & Conservation of Fluids
- Automated Alignment, Coupling, & Assembly Systems
- Autonomous Command & Control for Ground and Integrated Vehicle / Ground Systems

Environmental and Green Technologies
- Corrosion Prevention, Detection, & Mitigation
- Environmental Remediation & Site Restoration
- Preservation of Natural Ecosystems
- Alternate Energy Prototypes

Technologies to Increase Reliability and Mission Availability
- Advanced Launch Technologies
- Environment-Hardened Materials and Structures
- Inspection, Anomaly Detection & Identification
- Fault Isolation and Diagnostics
- Prognostics Technologies
- Repair, Mitigation, and Recovery Technologies
- Communications, Networking, Timing & Telemetry

Technologies to Improve Mission Safety/Mission Risk
- Range Tracking, Surveillance & Flight Safety Technologies
- Landing & Recovery Systems & Components
- Weather Prediction and Mitigation
- Robotics / Telerobotics
- Safety Systems

TA14 • THERMAL MANAGEMENT SYSTEMS

Cryogenic Systems
- Passive Thermal Control
- Active Thermal Control
- Integration & Modeling

Thermal Control Systems
- Heat Acquisition
- Heat Transfer
- Heat Rejection & Energy Storage

Thermal Protection Systems
- Entry / Ascent TPS
- Plume Shielding (Convective & Radiative)
- Sensor Systems & Measurement Technologies

Space Technology Roadmaps **STR • TABS**

TECHNOLOGY AREA BREAKDOWN STRUCTURE

Appendix E: Contributors

LEADERSHIP TEAM AND AUTHORS

Mason Peck
NASA Chief Technologist
Office of the Chief Technologist
NASA Headquarters

Faith Chandler
NASA SSTIP Development Manager
Office of the Chief Technologist
NASA Headquarters

Rob Anderson
Office of the Chief Engineer
NASA Headquarters

Harold Bell
Office of the Chief Engineer
NASA Headquarters

Jason Crusan
Human Exploration and
Operations Mission Directorate
NASA Headquarters

Chris Moore
Human Exploration and
Operations Mission Directorate
NASA Headquarters

Mike Moore
Science Mission Directorate
NASA Headquarters

David Moyer
Office of the Chief Technologist
NASA Headquarters

Harry Partridge
Office of the Chief Technologist
NASA Headquarters

Mark Redlinger
Office of the Chief Technologist
NASA Headquarters

James Reuther
Office of the Chief Technologist
NASA Headquarters

Anthony Strazisar
Aeronautics Research Mission
Directorate
NASA Headquarters

Calvin Williams
Mission Support Directorate
NASA Headquarters

Lindsey Bagley
The Tauri Group

Elaine Gresham
The Tauri Group

Rachael Lussos
The Tauri Group

Carie Mullins
The Tauri Group

John Nelson
The Tauri Group

Phil Smith
The Tauri Group

NASA CONTRIBUTORS

Mike Battaglia
Office of the Chief Technologist
NASA Headquarters

Keith Belvin
Center Chief Technologist
Langley Research Center

Stacey Brooks
Office of the Chief Technologist
NASA Headquarters

John Hines
Center Chief Technologist
Ames Research Center

Diana Hoyt
Office of the Chief Technologist
NASA Headquarters

Peter Hughes
Center Chief Technologist
Goddard Space Flight Center

Andrew Keys
Center Chief Technologist
Marshall Space Flight Center

Randy Lillard
Office of the Chief Technologist
NASA Headquarters

Dan Lockney
Office of the Chief Technologist
NASA Headquarters

Alexander MacDonald
Office of the Chief Technologist
NASA Headquarters

David McGowan
Office of the Chief Technologist
NASA Headquarters

Denise Podolski
Office of the Chief Technologist
NASA Headquarters

Julie Pollitt
Office of the Chief Financial Officer
NASA Headquarters

Kina Ratanjee
Office of the Chief Technologist
NASA Headquarters

Carl Ray
Office of the Chief Technologist
NASA Headquarters

Howard Ross
Center Chief Technologist
Glenn Research Center

John Saiz
Center Chief Technologist
Johnson Space Center

Karen Thompson
Center Chief Technologist
Kennedy Space Center

Ramona Travis
Center Chief Technologist
Stennis Space Center

David Voracek
Center Chief Technologist
Dryden Flight Research Center

Damian Taylor
Office of the Chief Technologist
NASA Headquarters

John Zmuidzinas
Center Chief Technologist
Jet Propulsion Laboratory

EXTERNAL CONTRIBUTORS

Paul Benda
Department of Homeland Security

Sam Black
Satellite Industry Association

Rebecca Blank
Department of Commerce

William F. Brinkman
Department of Energy

Glen Crawford
Department of Energy

Dan Hendrickson
Aerospace Industries Association

Marcos Heurta
Department of Energy

Steve Isakowitz
Virgin Galactic
Aerospace Industries Association

Robert Kavlock
Environmental Protection Agency

Kate Kronmiller
Orbital Sciences Corporation
Satellite Industry Association

Zachary Lemnios
Department of Defense

Sal Manno
Inmarsat
Satellite Industry Association

George C. Nield
Federal Aviation Administration

Bill Readdy
American Pacific Corporation

Alexander Saltman
Commercial Spaceflight Federation

SpaceX
Aerospace Industries Association

Ric VanderMeulen
ViaSat, Inc.
Satellite Industry Association

Julie Van Kleeck
Aerojet

Acronyms

AES	Advanced Exploration Systems
ALHAT	Autonomous Landing and Hazard Avoidance Technology
COTS	Commercial Orbital Transportation Services
CPST	Cryogenic Propellant Storage and Transfer
ECLSS	Environmental Control and Life Support System
EDL	Entry, Descent, and Landing
ESTO	Earth Science Technology Office
EVA	Extravehicular Activity
FDIR	Fault Detection and Isolation and Recovery
GNC	Guidance, Navigation, and Control
GSFC	Goddard Space Flight Center
HEOMD	Human Exploration and Operations Mission Directorate
HIAD	Hypersonic Inflatable Aerodynamic Decelerator
IRAD	Internal Research and Development
ISEP	Integrated Solar Energetic Proton
ISRU	In-Situ Resource Utilization
ISS	International Space Station
JPL	Jet Propulsion Laboratory
JSC	Johnson Space Center
KSC	Kennedy Space Center
kW	Kilowatt
LADEE	Lunar Atmosphere and Dust Environment Explorer
LEO	Low Earth Orbit
LIDAR	Light Detection And Ranging
MC-CAD	Monte Carlo Radiation Analysis of Detailed Computer Aided Design
Mbps	Megabits Per Second
MEMS	Microelectromechanical System
MISSE	Materials International Space Station Experiment

MMOD	Micrometeoroids and Orbital Debris
MSL	Mars Science Laboratory
mT	Metric Ton
NASA	National Aeronautics and Space Administration
NEA	Near-Earth Asteroid
NEO	Near-Earth Object
NEXT	NASA Evolutionary Xenon Thruster
NIAC	NASA Innovative Advanced Concepts
NRC	National Research Council
NTEC	NASA Technology Executive Council
OCIO	Office of the Chief Information Officer
OCT	Office of the Chief Technologist
OSMA	Office of Safety and Mission Assurance
PCOS	Physics of the Cosmos
PLSS	Portable Life Support System
PNT	Position, Navigation, and Timing
RBCC	Rocket Based Combined Cycle
RF	Radiofrequency
SARP	Software Assurance Research Program
SBIR	Small Business Innovation Research
SMD	Science Mission Directorate
SpaceX	Space Exploration Technologies Corp.
SPHERES	Synchronized Position Hold, Engage, Reorient Experimental Satellites
NASA SSTIP	Strategic Space Technology Investment Plan
STP	Space Technology Program
STTR	Small Business Technology Transfer
T/R	Transceivers/Receivers
TABS	Technology Area Breakdown Structure
TBCC	Turbine Based Combined Cycle
TDM	Technology Demonstration Missions
TPS	Thermal Protection Systems
TRL	Technology Readiness Level
VTB	Vertical Test Bed

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National Aeronautics and Space Administration

NASA Headquarters
300 E Street S.W.
Washington, DC 20024

www.nasa.gov