Coordinating Innovative Technology Development at NASA

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***Abstract*—Innovation requires continually using and coordinating new knowledge on the current, anticipated, and even unanticipated developments in a given area. You do not want to simply repeat what others are doing, so you must remain aware of other activities in your area of interest. You also have to maintain awareness of where the cutting edge is, because the limit of what's possible is continually pushed and redefined. Finally, "smart" innovation involves not only seeking innovative solutions to anticipated problems but also being prepared to respond to unanticipated problems or even unanticipated solutions.**

As the leading U.S. agency for aeronautics development, cutting-edge scientific discovery, and human space exploration, the National Aeronautics and Space Administration (NASA) must remain at the forefront of innovation. NASA enables innovation in technology development through a coordinated effort among its internal mission directorates and its partners in government, commercial, and academic sectors. As an independent office, NASA's Office of Technology, Policy, and Strategy (OTPS) provides the coordination effort necessary to ensure innovation.

OTPS uses and coordinates inputs from a broad community of experts. With these inputs, OTPS identifies and communicates shared needs and opportunities for partnership. OTPS provides strategic advice to synergize and ultimately facilitate innovative technology development both within and outside NASA.

This paper summarizes NASA's approach to ensuring innovation through a deliberately coordinated effort. In this paper, we first provide examples of how this coordination has enabled innovative technology development. We then describe how NASA's mission directorates use input from a broad community of experts to inform innovative technology development. Finally, we describe OTPS's role in coordinating inputs from both internal and external experts, including standardizing communication about technology developments, facilitating conversations with external partners on shared technology needs and solutions, and advising on strategies and policies to ensure innovative technology development. This paper can help members of the aerospace community understand their role in NASA's innovation efforts and how to engage OTPS in conversations about potential partnership.

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1. INTRODUCTION

Developing technology is an essential and enabling activity at NASA. Representing approximately 10 percent of NASA's budget,[1] technology development seeks a "solution that arises from applying the discipline of engineering science to synthesize a device, process, or subsystem, to enable a specific capability."[2] With a guiding vision to "discover and expand knowledge for the benefit of humanity,"[3] much of NASA's technology development involves layers of innovation: new devices, processes, or subsystems to enable new capabilities for making new discoveries.

To achieve this innovation, NASA relies on inputs from a broad community of experts in aerospace and related fields. NASA uses these expert inputs to determine which innovative solutions NASA needs, what potential partners need, and where opportunities to synergize innovative technology development efforts exist. These expert inputs help NASA pursue innovation that shows the limit of what's possible and how to push that limit. These expert inputs also enable "smart" innovation at NASA, using technology development approaches that not only address known limits but also account for unanticipated challenges and opportunities.

This paper reviews NASA's approach to innovation through the lens of NASA's mission directorates and the coordinating role of the Office of Technology, Policy, and Strategy (OTPS). Each of NASA's mission directorates use expert inputs, often through different means, to inform their technology development plans and decisions. Recently, NASA's organizational structure has changed, with the Human Exploration and Operations Mission Directorate restructured into the operations-focused directorate Space Operations Mission Directorate and the development-focused directorate Exploration Systems Development Mission Directorate. In addition, OTPS was formed through the integration of the Office of the Chief Technologist (OCT) and the Office of Strategic Engagements and Assessments (OSEA). The technology coordinating body role described in this paper was initially within OCT's mission and now is one of several focuses for the new Office of Technology, Policy, and Strategy. However, the technology development approaches published by the previous four mission directorates and OCT's coordinating role remains relevant. Therefore, this paper reviews the technology development approaches published by the previous four mission directorates as of early 2021:

- The **Aeronautics Research Mission Directorate (ARMD)** designs, develops, and tests technologies to improve aircraft and air transportation systems for the benefit of the American aviation industry, the passengers and businesses who rely on aviation, and the local and global environment affected by air transportation.[4]

- The **Space Technology Mission Directorate (STMD)** leads space technology research and development throughout the agency and with agency partners to enable exploration missions, such as missions planned for the Moon and Mars, and to enable technology transfer back into the U.S. economy.[5]

- The **Science Mission Directorate (SMD)** uses space-based observatories and robotic missions to answer science questions related to five disciplines—Earth Science, Planetary Science, Heliophysics, Astrophysics, and Biological and Physical Sciences—to fulfill national and international priorities for scientific discovery; inform future robotic and human space expeditions; and inspire science, technology, engineering, and mathematics (STEM) education nationwide.[6]

- The **Human Exploration and Operations Mission Directorate (HEOMD)** manages current space operations in low-Earth orbit and beyond, including activities on the International Space Station (ISS), launch services, commercial space transportation, human spaceflight capabilities, systems for human exploration in space and on planetary bodies, and transportation and communication for both human and robotic exploration programs.[7]

At the agency level, independent of the mission directorates, OTPS coordinates expert inputs from both within the mission directorates and throughout government, commercial, and academic sectors. OTPS uses these inputs to facilitate communication and partnership and provide strategic advice on innovative technology development, both within and outside NASA.

This paper summarizes NASA's approach to ensuring innovation through a deliberately coordinated effort. In this paper, we first provide examples of how this coordination has enabled innovative technology development. We then describe how NASA's mission directorates use input from a broad community of experts to inform innovative technology development. Finally, we describe OTPS's role in coordinating inputs from both internal and external experts, including standardizing communication about technology developments, facilitating conversations with external partners on shared technology needs and solutions, and advising on strategies and policies to ensure innovative technology development. This paper can help members of the aerospace community understand their role in NASA's innovation efforts and how to engage OTPS in conversations about potential partnership.

2. Coordinated Expert Input Enables Innovation at NASA

As the leading agency in cutting-edge scientific discovery, NASA faces diverse and evolving challenges and opportunities for technology development. As these challenges and opportunities are often influenced by other missions and discoveries, NASA must coordinate inputs from a broad community of scientific and technical experts to inform plans and decisions for innovative technology development.

In one example, NASA required an intensely coordinated effort for its 2018 InSight and MarCO missions to demonstrate an innovative application of an established technology. The InSight mission involved landing a robotic lander on Mars to expand our knowledge about rocky planet interiors. But NASA also used the flight for the InSight lander to demonstrate the new application of CubeSats in deep space. Building on the success of hundreds of CubeSats in Earth orbit, the Mars Cube One, or MarCO, showed that miniaturized deep space communication equipment can relay data from a planetary lander to Earth.[8] In fact, for the first time, the two MarCO CubeSats relayed telemetry data near-continuously as InSight successfully completed its entry, descent, and landing.

The innovative application successfully demonstrated by MarCO has since led to new opportunities for scientific discovery using constellations of CubeSats. For example, the new SunRISE mission uses a constellation of CubeSats as an aggregated aperture for a 10 km-baseline radio telescope to measure powerful eruptions from the Sun's atmosphere.[9] NASA's coordination of the Insight and MarCO missions enabled innovative opportunities for additional discovery.

With NASA continually gaining new knowledge from new discoveries, innovative technology development must account both for current expert inputs and for knowledge yet to be gained. One example of adapting innovation in response to new knowledge involves discoveries about the presence of water on the Moon. In 2008, with data from NASA's Moon Mineralogy Mapper (M3) aboard India's Chandrayaan-1, NASA first confirmed the presence of ice in the permanently shadowed craters near the Moon's poles.[10] This discovery affected plans for future human exploration of the Moon, including developing new technologies to extract water from the ice in the shadowed craters, where the temperature is near -250 degrees Fahrenheit. This discovery also inspired new uses for other NASA science missions, like the first use of the Stratospheric Observatory for Infrared Astronomy (SOFIA) to investigate the surface of the Moon. In 2020, SOFIA confirmed the presence of water molecules in sunlit areas of the Moon. In response to this better understanding of the presence of water on the Moon, human exploration architectures evolved again, considering new technologies for water extraction and new destinations for human settlement on the lunar surface. In addition, this discovery prompted more scientific inquiries, including new questions about how water is created and how it can persist in a harsh, airless environment.[11] These inquiries thereby prompt new areas of research for upcoming science missions, like the Volatiles Investigating Polar Exploration Rover (VIPER) planned for 2023.[12]

Given the nature of NASA's cutting-edge missions, innovation at NASA accounts for challenges and opportunities forecasted decades in advance. NASA plans missions that have timelines 10 to more than 30 years into the future. Many of these missions rely on technical and scientific discoveries that have yet to be realized. Therefore, NASA ensures innovation by coordinating expert input on anticipated technology needs and capabilities, while also conducting the experiments and demonstrations that inform the innovative development of those technologies over time.

For over 60 years, expert opinion has been that cryogenic fluid management (CFM) technologies are necessary for surface missions to the Moon in the 2020s and Mars in the 2030s. CFM technologies enhance system performance for key elements of human exploration architectures, including in-space propulsion, landers, and ascent vehicles. Although the planned applications of CFM technologies change with mission architectures over time, NASA continues to pursue innovation in CFM technologies. As of 2020, NASA has demonstrated a gauge for cryogenic storage on the ISS and has begun developing prototype components for cryogenic liquefaction on planetary surfaces.[13] As system components mature, NASA accounts for the new opportunities and new knowledge applicable to innovative CFM technology development.

In another example, NASA builds on over 70 years of supersonic flight research to demonstrate a new capability of quiet supersonic flight over land in the 2020s. Beginning in 2022, NASA plans to fly supersonic X-59 aircraft above U.S. communities to measure public response to the plane's quieter sonic boom. Data on the public response will be presented as regulatory officials consider lifting the 1973 ban on supersonic flight over land and define new allowable sonic boom levels with the international standards community.[14, 15] Knowledge gained over decades of research and development reveals new opportunities and challenges which then inform plans and decisions for innovative technology development.

Of course, just as new discoveries reveal new opportunities and challenges for innovation, successful innovation reveals new opportunities and challenges for discovery. For example, the introduction of cost-efficient "rideshare" launches has opened new opportunities for science missions with CubeSats, like the previously mentioned SunRISE. The increase in the number of CubeSats has also created a challenge for accurate identification and tracking of the standardized miniature satellites, affecting technology development plans in that area.[16] In another example, a material used for computer chips, monocrystal silicon, has the potential to reduce the mass of X-ray telescopes. These new optics may provide an opportunity for a lightweight telescope with two orders-of-magnitude greater sensitivity than the state-of-the-art and at a lower cost.[17] The potential of this innovative technological development affects science missions involving observations of exploded stars and black holes. Missions that might have already been decades in the making can evolve in response to innovation, and the changes in those missions might then necessitate changes in other technology development plans.

To achieve innovation, NASA draws on current expert knowledge, while planning decades in advance, and remains ready to change a technology development approach in response to new knowledge. Therefore, NASA's mission directorates each use, and update directorate-specific technology development plans informed by a broad community of experts, as described in the next section.

3. NASA Uses Expert Inputs to Plan Innovative Technology Development

NASA's mission directorates contribute to the agency's overarching goals through directorate-specific guiding objectives. Fulfilling each objective typically requires some level of innovative technology development, so the mission directorates use and update technology development plans. This section summarizes how each mission directorate develops its technology development plan (as of early 2021), while emphasizing the role of expert inputs in informing those plans.

Aeronautics Research Mission Directorate (ARMD)

A biennial Strategic Implementation Plan (SIP) details how ARMD expects to develop and advance technologies "to meet the needs of the aviation community, the Nation, and the world for safe, efficient, flexible, and environmentally sustainable air transportation."[18] ARMD's approach to technology development uses community dialogue and a trend analysis by subject matter experts and senior stakeholders.

This community dialogue includes domestic and international partners and experts from other government, commercial, and academic organizations. ARMD also incorporates inputs from reviews of ongoing research by federal advisory committees and the National Research Council's Aeronautics Research and Technology Roundtable. In addition, by partnering with the National Academies of Science, Engineering, and Medicine (NASEM), ARMD receives in-depth information on ARMD topics through NASEM's detailed studies.

With this community dialogue and the trend analysis, ARMD developed six "strategic thrusts." These strategic thrusts are areas of prioritization for aeronautics objectives: 1) safe, efficient growth in global operations; 2) innovation in commercial supersonic aircraft; 3) ultra-efficient subsonic transports; 4) safe, quiet, and affordable vertical lift air vehicles; 5) in-time system-wide safety assurance; and 6) assured autonomy for aviation transformation. In the 2019 SIP, ARMD details how these strategic thrusts help focus activities to prepare for potential futures.

Within each strategic thrust, ARMD determines measurable, community-level outcomes. These outcomes represent the envisioned capabilities made possible by ARMD's research, with contributions from key partners, phased across three periods: 2015 to 2025, 2025 to 2035, and beyond 2035. For example, under the second strategic thrust, innovation in commercial supersonic aircraft, ARMD envisions three phased outcomes: a supersonic overland certification standard in 2015 to 2025; affordable, low-boom, low-noise, and low-emission supersonic transport in 2025 to 2035; and increased utility and market growth of supersonic transport in 2035 and beyond. In each case, ARMD develops technologies with the expectation that partners will be able to continue innovation and incorporate the technologies into markets that have yet to emerge.

Space Technology Mission Directorate (STMD)

STMD takes a similar approach of working with a community of experts to identify trends that drive technology development decisions. STMD conducted a trend analysis to determine "major axes [of] change that have shaped, are shaping, and will continue to shape the global civilian space industry and civil space research over the next several decades."[19] The trend analysis involved a review of industry research, a literature review, an analysis of current technologies and their forecasted impacts, and discussions with STMD customers in HEOMD, SMD, and other government and industry organizations.[20]

With this trend analysis and ongoing community dialogue, STMD arrived at a list of four strategic thrusts: 1) *Go* with rapid, safe, and efficient space transportation; 2) *Land* with expanded access to diverse surface destinations; 3) *Live* with sustainable living and working farther from Earth; and 4) *Explore* with transformative missions and discoveries.[21]

STMD then developed outcomes for achieving the four strategic thrusts. For example, under the strategic thrust *Go*, STMD articulated three outcomes that result from innovative technology development in this area: nuclear technologies for fast in-space transit; cryogenic storage, transport, and fluid management technologies for surface and in-space applications; and advanced propulsion technologies for future science and exploration missions.[22] STMD then articulates the primary capabilities necessary to achieve these outcomes. For example, as of 2021, advanced propulsion and CFM are capabilities necessary to achieve the *Go* outcomes. STMD uses these capabilities to identify and prioritize gaps in technology development plans.

These plans incorporate a variety of expert inputs: insights from industry experts, specific capability needs as identified by SMD and HEOMD staff, and insights from NASA's principal technologists and Systems Capability Leadership teams—in-house subject matter experts who specialize in a given technology area. Consequently, innovative technology development decisions not only address capability gaps for STMD's two main customers—SMD and HEOMD—but also ensure innovations in areas that are a priority for NASA and the larger aerospace community.

Science Mission Directorate (SMD)

The Science Mission Directorate (SMD) uses the decadal survey process to define science priorities for more than 100 missions across five divisions. Developed by NASEM, the decadal surveys set high-level science priorities for specific disciplines, with guidance for achieving an envisioned 10-year program within the discipline. The results are broad strategic science goals. SMD then defines, develops, and forecasts innovative technologies necessary for realizing those goals.

The five most recent decadal surveys in each discipline guide each SMD division's plan for technology development:

- Astrophysics: *Astro2020: Decadal Survey on Astronomy and Astrophysics* (2020)
- Earth Science: *Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space* (2017)
- Heliophysics: *Solar and Space Physics: A Science for a Technological Society* (2013)
- Planetary Science: *Vision and Voyages for Planetary Science in the Decade 2013-2022* (2011)
- Biological and Physical Sciences: *Recapturing a Future for Space Exploration: Life and Physical Sciences Research for a New Era* (2011)

Each of these decadal surveys provide specific guidance on budgeting and prioritizing technology development.

For example, the decadal survey for Earth Science detailed recommendations for addressing, within the decade, the science community's highest priority concerns for Earth Science topics. The decadal survey described how the recommendations were primarily for NASA but also for the National Oceanic and Atmospheric Administration and the U.S. Geological Survey. The decadal survey's priorities came from a list of 35 key questions, derived from an initial list of 290 ideas from the science community, which a 20-member steering committee narrowed down with the help of five interdisciplinary panels. The committee then defined the objectives necessary to answer these 35 key questions, where "advances are most needed in both curiosity-driven and practically focused Earth science," and prioritized these objectives as "most important," "very important," and "important."[23] For example, the key question "How much will sea level rise, globally and regionally, over the next decade and beyond, and what will be the role of ice sheets and ocean heat storage?" is addressed by one of the "most important" objectives, such as "Determine the global mean sea-level rise to within 0.5 mm/yr over the course of a decade."[24] To do the science necessary to fulfill these objectives, SMD uses NASEM's recommendations—based on input from a national community of experts—to balance small, medium, and large missions, and their accompanying technology development needs, across the directorate's five divisions.

Human Exploration and Operations Mission Directorate (HEOMD)

Capability needs for human exploration architectures drive technology development at HEOMD. As of early 2021, HEOMD develops technologies that enable capabilities for missions in the Moon-to-Mars architecture. This architecture includes the Gateway orbiting lunar outpost, Artemis missions returning humans to the lunar surface building to a sustained human presence on the Moon, and a roundtrip human mission to Mars.[25] Because these missions have crosscutting capability needs, HEOMD works with NASA's internal community of experts to identify gaps in needed capability areas and the technologies needed to address those gaps.

HEOMD uses an annual capability data call and analysis to inform technology development plans and decisions. This data call goes to technical discipline experts from across NASA, including Systems Capability Leadership Team members, principal technologists from STMD, technology program executives from HEOMD, and technical fellows from NASA's Engineering and Safety Center.[26] The data call invites these experts to identify known gaps in capability areas, at the level of vehicles, systems, and components.

A Capability Integration Team (CIT) collects and analyzes the data call responses. At the beginning and again at the end of the data call process, the CIT works with HEOMD's human spaceflight architecture team, which defines requirements for human missions, to provide any additional capability gaps. Finally, the CIT maps the closure of capability gaps to the different architecture elements that then become possible. The 2020 data call found that 36 percent of the identified capability gaps required a technology development solution to achieve closure.[27]

For each mission directorate, recommendations from a broad community of experts drive plans and decisions for innovative technology development over decades. This community comprises both internal experts (such as the STMD principal technologists) and external experts (such as the steering committee members for NASEM's decadal surveys). Their expert inputs help NASA's mission directorates plan and achieve truly innovative technology development.

Coordinating the many different expert inputs informing each mission directorate is a challenge in itself. Coordinating the different technology development plans and decisions throughout the agency is a separate challenge, for which NASA instituted an independent office, described in the next section.

4. Outputs of OTPS Coordination Facilitate Innovative Technology Development

The coordination that ensures innovation in technology development at NASA is a massive and complex undertaking. The coordination efforts within each mission directorate are connected through a larger scale effort to inform agency-wide technology development plans and decisions. In addition to working with a broad community of experts, this agency-level effort involves working with U.S. Congress and the President's Administration, international partners, commercial partners, and the general public. Ultimately, this larger effort makes it possible for NASA to account for anticipated and unanticipated challenges and opportunities for innovative technology development. To undertake this effort, NASA empowered OTPS as an agency-level office independent of any mission directorate.

Under the prior OCT office several coordination products and initiatives were undertaken to facilitate smart innovative technology development across NASA. These OCT products, described below, remain influential across NASA's mission directorates, and OTPS is currently in the process of incorporating them into a broader set of strategic priorities.

OTPS integrates inputs from NASA's mission directorates to identify best practices for innovative technology development planning and decision making. OTPS then communicates these best practices back to the mission directorates, to inform their ongoing technology development planning efforts, and to agency-level decision makers in NASA and other government agencies. To enhance the identification and communication of these best practices, OTPS conducts targeted studies and activities. One output from OCT's prior activities is the Technology Taxonomy.

NASA uses the Technology Taxonomy to standardize communication about technology needs and capabilities. To develop the 2020 version of the Technology Taxonomy, OCT worked with NASA's Center Technology Council to coordinate input from internal experts, including technical fellows, Systems Capability Leaders, and principal technologists. A taxonomy draft was then circulated throughout the agency to collect feedback and then made available for public review and comment. The final version comprised 17 discipline-based technology areas, which were further broken down by subareas and then technology types within the subareas.

The taxonomy is a foundational element of NASA's technology management process. NASA's mission directorates reference the taxonomy to solicit technology development proposals, inform decisions on technology policy and prioritization, and communicate internally and externally about opportunities to synergize innovative technology development. The Technology Taxonomy also provides the organizing structure for NASA's technology tracking database TechPort, which makes data on more than 12,000 technology projects searchable and available to the public.[28]

In addition to integrating inputs internally from NASA's mission directorates, OTPS also coordinates inputs externally from other government agencies that prioritize innovative technology development, especially as related to aerospace. With these inputs, OTPS identifies technology needs and capabilities of mutual interest and facilitates conversations about partnership opportunities. The main output of this activity is participation in the S&T Partnership Forum.

As a member of the S&T Partnership Forum, OTPS works with representatives and experts from other organizations to identify technology solutions to joint challenges. Established in 2015, this forum is an interagency initiative to synergize innovative technology development across space agencies. As an informal collaboration between NASA, the Department of Defense, and the Intelligence Community, the forum enables joint capability studies, sharing of technology roadmaps, and Technical Interchange Meetings focused on S&T topics of mutual interest,[29] such as in-space assembly technologies[30] and trusted autonomy.[31] Through its participation in the forum, OTPS helps NASA optimize its partnerships and investments, by facilitating the sharing of knowledge and resources, reducing duplication in technology development, and coordinating expert inputs on technology development needs and capabilities.[32]

Finally, OTPS coordinates and promotes innovation among NASA's own expert workforce. To connect NASA's workforce to tools and strategies for increasing the pace of innovation, the prior OCT office used a five-part framework: 1) *clarify the need* by defining challenges to increase the diversity of ideas; 2) *assess the ecosystem* by developing mechanisms to determine who and what can help address the challenges; 3) *define the future state* by expanding the vision to sustain innovation and establish the "why"; 4) *develop, communicate, and coordinate experiments* focused on learning; and 5) *share lessons learned* to ensure we fail smart. Using this framework, OCT produced such outputs as an agency-wide cloud-based innovation portal; risk leadership strategies to assess NASA's risk portfolio; co-opetition challenges, combining the best aspects of competition and collaboration; and innovation experiments, to promote the mindset among NASA's workforce that failure provides valuable knowledge and a tool for future success.

Again, essential to all of these innovation-enabling activities is the coordination of inputs from a broad community of experts, both internal and external to NASA. Using these inputs, OTPS advises and advocates for innovative technology development that pushes against the boundaries of unforeseen challenges, while also promoting the synergistic development of technologies to address known challenges. OTPS creates an integrated view of what technology opportunities and challenges are possible now and in the anticipated and unanticipated future.

5. CONCLUSION

This paper highlighted NASA's approach to smart innovation. Each mission directorate has their own objectives and approach for achieving innovative technology development; however, across the agency, NASA relies on input from external experts. As an inclusive, community-driven endeavor, innovation at NASA provides many opportunities for members of the aerospace community and related fields to contribute their expertise. OTPS supports coordination and analysis of this innovation and offers an independent body to support cross-agency engagement on emerging science and technology topics. OTPS relies on expert input to inform innovative technology development plans and decisions across the agency. Experts seeking to provide input can reference the OCT-developed Technology Taxonomy and published technology development plans of the mission directorates to identify areas of common interest and opportunities for partnering. OTPS welcomes any interested parties and is happy to help potential contributors identify and connect with appropriate organizations across the agency.

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REFERENCES

[1] Conde, A. (29 October 2019). "An update to the NASA Advisory Council." NASA Advisory Council October 2019 Meeting https://www.nasa.gov/sites/default/files/atoms/files/acon de_oct_oct2019_508.pdf Accessed 3 January 2022.

[2] NASA Office of the Chief Technologist. (2017). NASA Strategic Technology Investment Plan. https://www.nasa.gov/sites/default/files/atoms/files/201 7-8-1_stip_final-508ed.pdf Accessed 3 January 2022.

[3] NASA (2021) Our Missions and Values. https://www.nasa.gov/careers/our-mission-and-values, Accessed 3 January 2022.

[4] NASA ARMD (2020) About Aeronautics Research Mission Directorate (ARMD). https://www.nasa.gov/aeroresearch/about-armd Accessed 9 April 2021.

[5] NASA STMD (2020) Space Technology Mission Directorate: About Us. https://www.nasa.gov/directorates/spacetech/about_us/i ndex.html Accessed 9 April 2021.

[6] NASA SMD (2021) About Us: NASA's Science Vision https://science.nasa.gov/about-us/smd-vision Accessed 9 April 2021.

[7] NASA HEOMD (2021) About the Human Exploration and Operations Mission Directorate. https://www.nasa.gov/directorates/heo/about.html Accessed 9 April 2021.

[8] NASA InSight Mission Overview. https://mars.nasa.gov/insight/mission/overview/ Accessed 3 January 2022.

[9] University of Colorado Boulder (2020) Sun Radio Interferometer Space Experiment (SunRISE). https://www.colorado.edu/ness/projects/sun-radio-interferometer-space-experiment-sunrise Accessed 3 January 2022.

[10] NASA (2018) Ice Confirmed at the Moon's Poles. https://www.nasa.gov/feature/ames/ice-confirmed-at-the-moon-s-poles Accessed 3 January 2022.

[11] NASA (2020) NASA's SOFIA Discovers Water on Sunlit Surface of Moon. https://www.nasa.gov/press-release/nasa-s-sofia-discovers-water-on-sunlit-surface-of-moon Accessed 3 January 2022.

[12] NASA (2020) VIPER Mission Overview. https://www.nasa.gov/viper/overview Accessed 3 January 2022.

[13] Hansen, H. C., Johnson, W. L., Meyer, M., Werkheiser, A., & Stephens, J. R. (2020) Cryogenic Fluid Management Technologies Enabling for the Artemis Program and Beyond. In ASCEND 2020 (p. 4000).

[14] NASA ARMD (2019) NASA Aeronautics Strategic Implementation Plan (2019). https://www.nasa.gov/sites/default/files/atoms/files/sip-2019-v7-web.pdf Accessed 3 January 2022.

[15] NASA ARMD (2020) Progress in 2020 Advances Aviation's Future. https://www.nasa.gov/aeroresearch/progress-in-2020-advances-aviations-future Accessed 3 January 2022.

[16] NASA (2020) 13.0 Identification and Tracking Systems. https://www.nasa.gov/smallsat-institute/sst-soa-2020/identification-and-tracking-systems Accessed 3 January 2022.

[17] NASA (2019) NASA's New Lightweight X-ray Mirrors Ready for Try-outs in Space. https://www.nasa.gov/feature/goddard/2019/nasa-s-new-lightweight-x-ray-mirrors-ready-for-try-outs-in-space Accessed 3 January 2022.

[18] NASA ARMD (2019) NASA Aeronautics Strategic Implementation Plan (2019). Page 7. https://www.nasa.gov/sites/default/files/atoms/files/sip-2019-v7-web.pdf Accessed 3 January 2022.

[19] Earle, K. D., Carrier, M., Cirillo, W., Grande, M. L., Jones, C. A., Judd, E., ... & Stafford, M. (2018). Strategic Framework for NASA's Space Technology Mission Directorate. In 2018 AIAA SPACE and Astronautics Forum and Exposition (p. 5136).

[20] Grande, M. L., Carrier, M., Cirillo, W., Earle, K. D., Jones, C. A., Judd, E., ... & Stafford, M. (2018). Mega-Drivers to Inform NASA Space Technology Strategic Planning. In 2018 AIAA SPACE and Astronautics Forum and Exposition (p. 5137).

[21] Engelund, W. & McDonald, M. (3 February 2021). "STMD Strategic Framework Overview."

[22] Engelund, W. & McDonald, M. (3 February 2021). "STMD Strategic Framework Overview."

[23] National Academies of Sciences, Engineering, and Medicine (2019) Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space: An Overview for Decision Makers and the Public. Washington, DC: The National Academies Press.

https://doi.org/10.17226/25437.

[24] National Academies of Sciences, Engineering, and Medicine (2018) Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space. Washington, DC: The National Academies Press. https://doi.org/10.17226/24938.

[25] NASA (2020) NASA's Lunar Exploration Program Overview. https://www.nasa.gov/sites/default/files/atoms/files/artemis_plan-20200921.pdf Accessed 9 April 2021.

[26] Benjamin, G., Burg, A., Boggs, K. G., McVay, E., Goodliff, K., & Elburn, D. (2021) Exploration capabilities data analysis: An integrated approach. IEEE.

[27] Benjamin, G., Burg, A., Boggs, K. G., McVay, E., Goodliff, K., & Elburn, D. (2021) Exploration capabilities data analysis: An integrated approach. IEEE.

[28] NASA (2021) NASA TechPort Search Results on April 9, 2021. https://techport.nasa.gov/search Accessed 9 April 2021.

[29] Betser, J., Ewart, R., & Chandler, F. (2016) Science and Technology (S&T) Roadmap Collaboration between SMC, NASA, and Government Partners. In AIAA SPACE 2016 (p. 5228).

[30] Hamill, D., Jefferies, S. A., Moses, R. W., Stillwagen, F., Mullins, C., & Gresham, E. (2018). Space Science and Technology Partnership Forum: Analysis for a Joint Demonstration of High Priority, In-Space Assembly Technology. In 2018 AIAA SPACE and Astronautics Forum and Exposition (p. 5307).

[31] NASA (2019) Trusted Autonomy for the Moon and Mars. https://www.nasa.gov/offices/oct/feature/Trusted_Autonomy_for_the_Moon_and_Mars Accessed 3 January 2022.

[32] NASA OCT (2020) Science and Technology Partnership Forum. https://www.nasa.gov/offices/oct/science-and-technology-partnership-forum.html Accessed 3 January 2022.

BIOGRAPHY

***Erica Rodgers** leads Science and Technology Partnerships within NASA's Office Technology, Policy, and Strategy. Rodgers establishes government-wide collaboration frameworks in technology areas where interagency teamwork is beneficial. Rodgers previously served as an aerospace engineer at NASA's Langley Research Center, where she performed systems analysis of Mars exploration architectures. Prior to joining NASA, Rodgers worked in academia for 18 years. Rodgers taught astronomy and astrophysics at several colleges and universities, performed research of solar X-rays and their impact on Earth's upper atmosphere and of dust grain environments surrounding forming stars, and developed and launched science instrumentation. Rodgers worked in the aerospace industry for three years in parallel with conducting research, in systems engineering and satellite operations. Rodgers received her PhD in space physics from the University of Alaska Fairbanks, and her BS and MS in aerospace engineering from the University of Colorado at Boulder.*