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Roundtable Proceedings: Ways Forward for On-Orbit Servicing, Assembly, and Manufacturing (OSAM) of Spacecraft

Sara A. Carioscia
Benjamin A. Corbin
Bhavya Lal

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IDA SCIENCE & TECHNOLOGY
POLICY INSTITUTE
1701 Pennsylvania Ave., Suite 500
Washington, DC 20006-5805

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For More Information:

Bhavya Lal, Project Leader
blal@ida.org, 202-419-3724

Mark J. Lewis, Director, IDA Science and Technology Policy Institute
mjlewis@ida.org, 202-419-5491

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Executive Summary

Launch from Earth imposes significant limitations on the size, volume, and design of spacecraft: spacecraft need to be accommodated as a payload in the fairing of a single launch vehicle, the volume of which may restrict the size and number of instruments that can be included for science and national security missions; components must be ruggedized to withstand the harsh launch environment, which imposes penalties in terms of mass and size, limiting payload capabilities and increasing complexity, test time, and cost; and backups and redundancies must be included to provide contingencies against damage during launch or failure on orbit. The limitations associated with spacecraft architectures where components are fully assembled on Earth can thus constrain the design, capabilities, lifespan, and products of space systems. Additionally, once an asset is in space, it typically cannot be refreshed or improved (e.g., its sensors cannot be replaced with new technology to increase its capabilities).

On-orbit servicing, assembly, and manufacturing (OSAM) technologies have been suggested and, at different levels, pursued to overcome these limitations—an example of this is the International Space Station. It has been argued that a wide variety of space missions could benefit from these technologies; however, remaining challenges, related to both technology development and the surrounding policy framework, may restrict the growth of these activities.

In 2017, at the request of the White House Office of Science and Technology Policy, a team of researchers at the IDA Science and Technology Policy Institute (STPI) examined the implications of on-orbit manufacturing and assembly of spacecraft to supplement the current terrestrial-based approach. Stakeholders who provided input to the study recommended a forum to discuss the findings and next steps for these activities. To provide an opportunity for these and other subject matter experts at Federal agencies, companies, and non-profits involved in OSAM to discuss key technical and policy issues, STPI, with the support of the White House Office of Science and Technology Policy and the National Space Council, hosted a day-long workshop on the challenges, next steps, and roles and responsibilities of government and private industry for OSAM of spacecraft on May 31, 2018 at the Eisenhower Executive Office Building in Washington, D.C. The 30 attendees represented 9 industry organizations, 7 government organizations, and 4 non-profit organizations (including Federally Funded Research and Development Centers, University Affiliated Research Centers, and universities).

Prior to the roundtable, STPI sent a questionnaire asking roundtable attendees to identify key challenges in the development of OSAM—including technology, policy, legal, and regulatory viewpoints—and specific drivers that create these challenges and potential pathways to address them. The questionnaire also solicited information regarding the roles of the government and industry in furthering these development efforts. Responses to these questions were used to guide discussions facilitated during the roundtable discussion, which were moderated by STPI staff. This report offers a summary of the findings from that workshop, as well as an analysis of the questionnaire responses.

For the purposes of this report, *servicing* is defined as the on-orbit alteration of a satellite after its initial launch, using another spacecraft to conduct these alterations; *assembly* involves the on-orbit aggregation of components to constitute a spacecraft; and *manufacturing* involves the on-orbit transformation of raw materials into usable spacecraft components.

Survey respondents agreed overall that OSAM has two main application areas: enabling larger modular structure and platforms than currently feasible, and improving the management of legacy and upcoming fleets of satellites. Specific application areas that could benefit from OSAM activities included satellite communications, signals and communications intelligence, commercial facilities on orbit, crewed and robotic space exploration, astrophysics, remote sensing, space-based intelligence, surveillance, and reconnaissance (ISR), space situational awareness (SSA), position, navigation, and timing (PNT), and missile warning systems. Stakeholders expected to benefit included both government (Air Force Space Command, the National Reconnaissance Office, the Intelligence Community, NASA science and human exploration directorates, and other civil space organizations) and commercial (satellite fleet owners and operators, service providers, and manufacturers) entities.

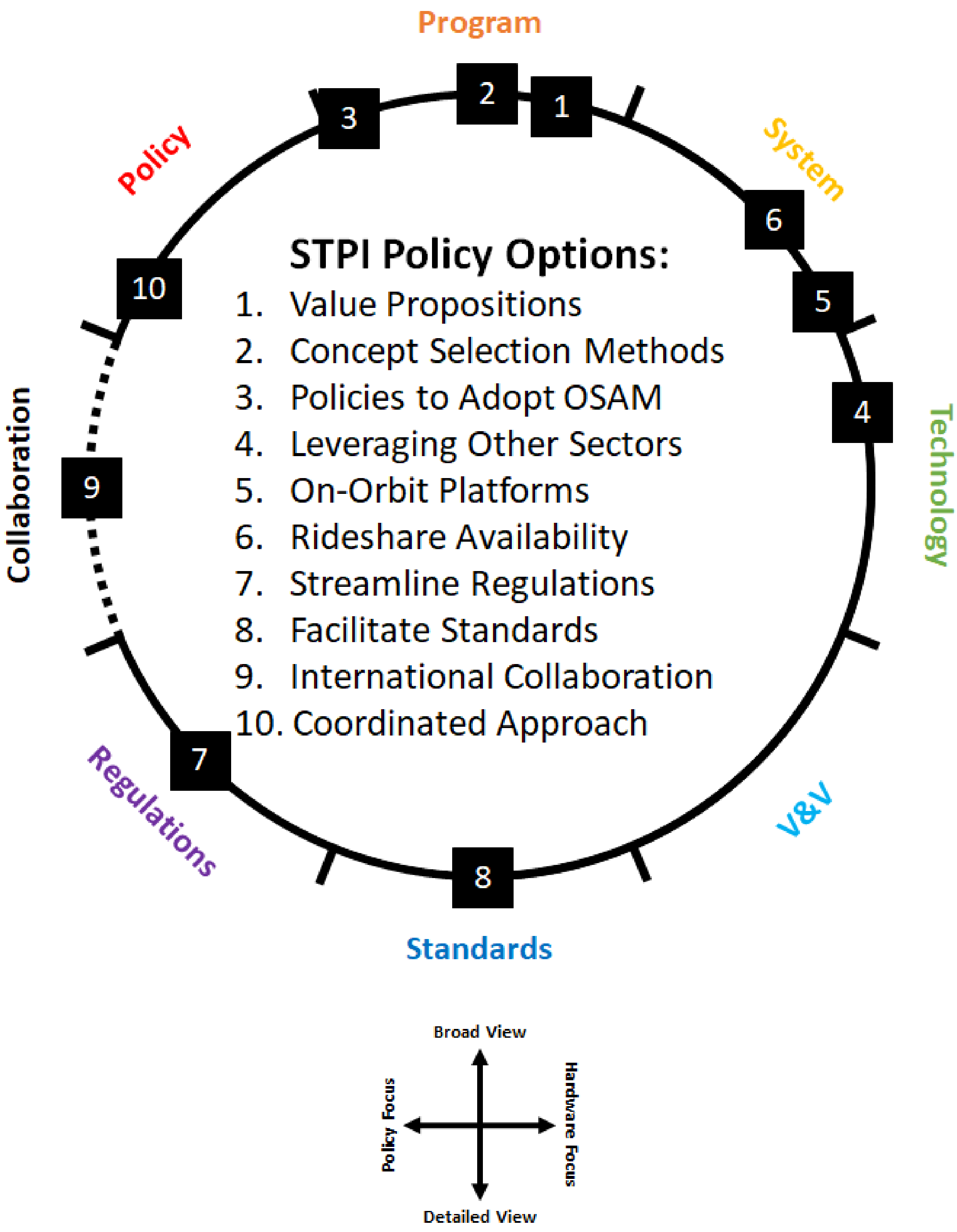
Attendees of the roundtable discussion generally agreed that the main challenges to developing and implementing OSAM technologies and activities exist at both the programmatic and system levels, as well as in the establishment of standards and practices. Some examples of these include the lack of expression of value propositions for OSAM activities, the culture of single-launch single-use missions, and the need for common interfaces as well as remote validation and verification. OSAM activities also face challenges in policy, regulations, and international obligations. Attendees agreed that the significant issues preventing OSAM technologies from moving forward are: the lack of coordination in the U.S., both within government and between government and other stakeholders; the absence of a system through which to establish and adopt standards; and the lack of a clear regulatory environment for future technologies and approaches.

The roundtable participants identified several ways forward to support U.S. efforts in OSAM. One of these is a strategic plan, which would need to be well-supported by resources and sufficiently high-level to avoid being prescriptive. Another would be for the

President of the United States to sign an Executive Order asserting OSAM as an area of critical national importance. Others include scaling up efforts to facilitate standards (e.g., organizations like CONFERS), establishing common definitions and terminology, increasing international collaboration, and spinning-in technologies from other terrestrial sectors such as robotics and automation.

After analyzing the questionnaire responses and the roundtable discussions, STPI developed a model that characterizes the discussions, challenges, drivers, and pathways forward into one of eight broad categories. STPI also examined existing and planned missions, studies, and partnerships and mapped them onto the model. Finally, STPI identified policy options for OSTP to pursue in OSAM that will ensure U.S. leadership in this area:

- Conduct analyses to evaluate the value propositions of OSAM and identify if there are missions where OSAM approaches yield scientific, economic, or other benefits.
- Revisit space systems concept selection methodologies to better articulate and characterize the value and risk from non-traditional space mission concepts.
- If these value propositions prove that OSAM can deliver value, work with government organizations to develop space system concept selection methodologies, practices, and policies that will encourage the adoption of OSAM approaches.
- Encourage consideration of technologies and approaches that can be leveraged from terrestrial sectors to benefit OSAM and future space activities.
- Ensure the availability of on-orbit platforms for the development of OSAM technologies and approaches.
- Promote and enable rideshare technology experiments for OSAM on government missions.
- Review, clarify, and, where possible, simplify and streamline all licensing policies and regulations relevant to OSAM activities.
- Using transparency and confidence building measures, facilitate the development of standards and norms of behavior for OSAM with the private sector and aerospace industry associations.
- Encourage international collaboration across OSAM activities.
- Develop a coordinated approach, though not a formal strategy or roadmap, to better align government and industry efforts in OSAM.



STPI's policy options mapped to a model characterizing the topics of discussion

Contents

1. Introduction

In 2017, at the request of the White House Office of Science and Technology Policy (OSTP), a team of researchers at the IDA Science and Technology Policy Institute (STPI) examined the potential implications of on-orbit manufacturing and assembly of spacecraft to supplement the current terrestrial-based approach. We conducted three specific tasks: (1) identify—with quantification to the extent feasible—space missions involving science, exploration, national security, and commercial activity where the payoff of orbital manufacturing and assembly is notable; (2) review the state of the art and future trends of the area from a global perspective; and (3) propose next steps from a U.S. perspective in accelerating progress, from the points of view of both technology and policy.[1] At the end of the project, stakeholders who provided input to the study recommended that there be a forum to discuss next steps.

Based on this feedback, and with the support of OSTP and the National Space Council, STPI held a daylong workshop on the challenges, next steps, and responsibilities (government and industry) for on-orbit servicing, assembly, and manufacturing (OSAM) of spacecraft on May 31, 2018 with participation from 30 representatives and subject matter experts from 9 industry organizations, 7 government organizations, and 4 non-profit organizations (Federally Funded Research and Development Centers, University Affiliated Research Centers, and universities). The main goals of the roundtable were three-fold:

- Identify space missions that could benefit most from OSAM and why;
- Discuss steps the private sector and the Federal Government could take to ensure that the United States is a global leader in OSAM;
- Consider whether developing a national strategy on OSAM would be a productive next step.

Prior to the roundtable, STPI sent a questionnaire asking roundtable attendees to identify what they saw as the key challenges in the development of OSAM—from technology, policy, legal, and regulatory viewpoints—as well as specific ways forward. The questionnaire also solicited information regarding the roles of the government and industry in furthering these development efforts. Responses on these topics were used to guide discussions during the roundtable. The roundtable itself provided an opportunity for

[1] Boyd, Iain D., Reina S. Buenconsejo, Danielle Piskorz, et al. 2017. "On-Orbit Manufacturing and Assembly of Spacecraft." Washington, D.C.: Science and Technology Policy Institute. https://www.ida.org/idamedia/Corporate/Files/Publications/STPIPubs/2017/P-8335.pdf

subject matter experts at Federal agencies, non-profits, and companies involved in OSAM to discuss key technical and policy issues related to the development and use of activities enabling and involving the on-orbit servicing, assembly, and manufacturing of spacecraft. The main topics and takeaways from this discussion are offered in Chapter 3.

Chapter 2 is a summary of attendee responses to the pre-roundtable questionnaire. Chapter 3 provides an overview of the workshop discussion. Chapter 4 is a summary of what STPI sees as the next steps in the process. Appendix A lists the names and affiliations of all roundtable participants. Appendix B provides the agenda for the roundtable discussion. A copy of the questionnaire and a high-level analysis of the responses are provided in Appendices C and D.

All perspectives and conclusions contained in this workshop report are non-attributional views provided by roundtable attendees in questionnaire responses and roundtable discussions.

For the purposes of the roundtable discussion and questionnaire, the following definitions were developed:

- **Servicing** involves the on-orbit alteration of a satellite or its orbit after its initial launch using another spacecraft to conduct these alterations. Examples include relocating the satellite to a new orbit, refueling, repairing broken parts, replacing parts, deploying systems that failed to deploy after launch, and cleaning components.
- **Assembly** involves the on-orbit aggregation of components to constitute a spacecraft into a new shape or configuration, especially (but not exclusively) considering shapes and configurations that cannot be achieved with traditional deployment methods and available launch vehicles. The spacecraft can be assembled by itself with a robotic arm, by a free-flying companion spacecraft (i.e., a spacecraft that launches along with the satellite), or by a third-party spacecraft (i.e., one that is later commissioned to act on a spacecraft). Components can be launched from the ground or manufactured on orbit.
- **Manufacturing** involves the on-orbit transformation of raw materials into usable spacecraft components. The raw materials can be launched from the ground or harvested in space. Manufacturing typically focuses on additive manufacturing but is not limited to this process.

2. Summary of Questionnaire Results

A. Questionnaire Overview

STPI developed a questionnaire for participants to complete in advance of the meeting, in order to learn more about the participants and their ideas regarding the challenges in OSAM, as well as to establish a basis for starting and framing the discussions during the roundtable. The questionnaire consisted of 18 questions including: information about the questionnaire respondents and the organizations they represent; respondent views of key challenges, drivers, and pathways forward in the technology and policy development of OSAM; lessons learned from space missions as well as other sectors (e.g., robotics, cybersecurity); roles of government and industry; and thoughts on the use of a national strategy or roadmap for OSAM. The questionnaire can be found in Appendix C.

STPI received 40 responses, 27 of which were complete and 13 of which were partially complete. Not all participants answered all questions, and most questions were open-ended, allowing respondents to provide varying levels of detail in their answers. Because some individuals who completed the questionnaire were unable to attend in person, the questionnaire responses include input from some who did not participate in the roundtable.

In this chapter, our analysis of the questionnaire responses is grouped by topic, rather than by question order, to provide a more concise flow of information gained from the questionnaire respondents. A detailed summary of the responses to each question in the order that they appear in the questionnaire can be found in Appendix D.

B. Workshop Information

STPI first asked respondents what organizations they represent (Question 1) and in what areas respondents are currently working or have expertise (Question 2). This information was used to assess the different sectors and specialties of the workshop participants. STPI classified the organizations listed in response to Question 1 as government, industry, non-profit, or academia. The respondents almost equally represented government (6 NASA, 8 DOD) and industry (13 responses from 9 different companies).

Respondents were asked to identify their areas of expertise to provide some background for the analysis of their answers. STPI allowed respondents to select multiple of the following five areas: Servicing, Assembly, Manufacturing, Policy/Regulatory, or Other. Respondents were asked to provide additional details for Other responses; the 13 Other responses that were submitted included variations on the following: interagency collaborations, on-orbit inspection, international standards, missions or systems architecture, systems engineering, technology, cyber security, optimization, and aerospace engineering.

Question 3 asked private sector respondents about their company's internal research and development (IRAD) expenditures in 2017 for OSAM activities. Responses ranged from less than $1M to more than $10M, with a total investment from those that responded in excess of $50M.

Question 17 asked what products or outcomes they would like to see emerge from the workshop. Many indicated that beginning a roadmap or an outline of steps to pursue a roadmap would be a desired result. Some respondents focused on establishing avenues for collaboration, cooperation, and advocacy moving forward. Others offered specific suggestions to improve OSAM efforts in the U.S. (e.g., steps to establish a shared knowledge base, to be used by government as well as private entities; common definitions of on-orbit servicing, assembly, manufacturing, and related terms and technologies).

Question 18 asked about other topics not addressed in the questionnaire that were relevant to the OSAM roundtable discussion. Respondents included international participation and norms of behavior as well as greater understanding of budgets available for OSAM technology development and activities.

C. OSAM Benefits and Applications

Question 4 asked what types of space activities or stakeholders are expected to benefit most from OSAM. Within government, benefitting stakeholders include Air Force Space Command, National Reconnaissance Office (NRO), the Intelligence Community (IC), NASA science and human exploration directorates, and other government organizations that fly Earth Observation and remote sensing satellites (e.g., Department of Commerce/National Oceanic and Atmospheric Administration/U.S. Geological Survey). Within industry, satellite fleet owners and operators, service providers, and manufacturers stand to gain from OSAM.

The application areas of OSAM that respondents identified fell into two broad categories: enabling larger modular structures and platforms than currently possible, and improved management of legacy fleets. Specific application areas included satellite communications, signals and communications intelligence, commercial facilities on orbit, crewed and robotic space exploration, astrophysics, remote sensing, space-based intelligence, surveillance, and reconnaissance (ISR), space situational awareness (SSA), position, navigation, and timing (PNT), and missile warning systems.

Other advantages of OSAM could include lower costs, increased performance, longer satellite life, decreased technology refresh time, increased resilience, better asset management, and more sustainable spaceflight operations.

D. Challenges, Drivers, and Pathways in Technology and Programs

Questions 5, 6, and 7 asked respondents to identify the key challenges in *technology development* related to OSAM activities, the drivers of those challenges, and specific pathways that could address those challenges. Although some responses were specific to one of the three activities (servicing, assembly, or manufacturing), most of the responses related to all three topics. Responses were at a high level and included areas that affect technology investments.

STPI organized the responses related to all three topics into three broad categories: program level challenges, system level challenges, and standards and practices. Program level challenges included the current systems engineering engine not being suited for OSAM design activities, a lack of expression of value propositions and clear business cases for OSAM mission activities, the lack of a launch cadence to geostationary orbit (GEO), and the need for stakeholders to change their cultures to accommodate OSAM activities (e.g., single-launch mindset). System level challenges included robotics and AI, cybersecurity, and testing, while challenges regarding standards focused on common interfaces, remote validation and verification, and use of modular systems.

The maturity of relevant technologies was not cited as the primary issue for OSAM activities moving forward. In servicing technology development challenges were primarily related to the lack of cooperation—both the fact that most existing satellites were not designed to be serviced, as well as the lack of clarity regarding what it means to be "serviceable." Issues in assembly were primarily systems level challenges related to assembly procedures, optimization, and precision. For manufacturing, respondents did point to basic technology challenges related to materials development for space applications, manufacturing increasingly complex and dense components for spacecraft, and recycling technology.

E. Challenges, Drivers, and Pathways in Policy, Law, and Regulations

Questions 8, 9, and 10 asked respondents to identify the key challenges in *policy, law, or regulations* related to OSAM activities, the drivers of those challenges, and specific pathways that could address those challenges. Most responses applied to all three topics with little differentiation between servicing, assembly, and manufacturing.

STPI organized the responses into four broad categories: policy, standards, regulations, and treaty and international obligations (see model introduced in Chapter 4). These focused on a lack of coordination in the U.S. (both within the government and between government, industry, and other stakeholders); the absence of a system through which to establish and adopt standards; and the lack of a clear regulatory environment for future technologies and activities (e.g., debris removal, salvage rights, and subtractive manufacturing debris standards).

F. Lessons Learned

Question 11 asked respondents about past lessons from space activities as well as activities outside the space sector that can be drawn from to address current challenges in OSAM. Responses focused on ensuring adequate levels of investment, taking a broad approach to OSAM activities, and establishing norms of behavior in space. Additionally, many respondents noted the value of applying lessons and technologies from non-space sectors to space and to OSAM specifically (e.g., different types of manufacturing) as well as the importance of including personnel with many different areas of expertise in the development teams for each of these projects.

G. OSAM Roadmap and Milestones

Question 13 asked if a formal interagency roadmap or strategy for OSAM would be useful. Of the 19 respondents to this question, 11 said that such a roadmap would be useful and one said it would not be useful. The remaining 7 asserted that a roadmap would be useful to varying extents under specific circumstances (e.g., if it is backed with adequate resources; it is kept high-level; it is used for policy but not technology).

Question 14 asked what milestones would be expected from such a roadmap or what else could be done to facilitate necessary progress. These milestones included funding, organizational changes (e.g., creation or expansion of groups to facilitate coordination), and the establishment of standards and regulations.

H. Roles of Government and Industry

Question 12 asked respondents about the roles of government in the emerging field of OSAM. Generally, responses indicated that the government should allocate sufficient funding to both technology development efforts pursued solely by government as well as those pursued through partnerships within government (e.g., NASA with USAF) as well as with non-governmental organizations (e.g., industry, university). In addition, government should drive the development of regulations as well as standards, including industry and other involved entities in the establishment of these systems.

Question 15 asked respondents about the roles of private industry in the emerging field of OSAM. These roles included developing and supporting business models, cooperating and communicating with other private and governmental entities, and working to establish standards, both domestic and international.

3. Overview of Workshop Discussion

The roundtable included five moderated sessions focused on: (1) challenges and ways forward for on-orbit servicing; (2) challenges and ways forward for on-orbit assembly; (3) challenges and ways forward for on-orbit manufacturing; (4) government role in OSAM; and (5) industry role in OSAM. The discussions were moderated by STPI research staff.

This chapter summarizes the non-attributional views, opinions, and dialogue of the roundtable attendees during the event. The major findings, and debates are organized into eleven overarching topics areas: (1) value propositions and applications; (2) business cases; (3) funding; (4) coordination, communication, and standards; (5) verification and validation; (6) technology; (7) cultural issues; (8) policy and regulations; (9) OSAM Roadmap; (10) roles of government; and (11) roles of industry. Findings are subdivided within those topic areas as appropriate. Findings specific to servicing, assembly, or manufacturing are categorized as such; the first category of each section includes those findings that are applicable to all three activities collectively. Note that this is a summary of the discussion and is not STPI's assessment of the findings. STPI's views are presented in Chapter 4.

A. Value Propositions and Applications

Servicing, Assembly, and Manufacturing

- On-orbit activities via modular designs will make adding or switching payloads easier, allowing updates to existing platforms and offering financial benefits (e.g., lower up-front cost, delayed instrument development costs, earlier revenue streams, better utilization of opportunities, and the ability to respond to changing market conditions).
- Because the United States is so far ahead in the complex systems engineering management required for space-based activities, many nations are interested in collaborating with the U.S. in space. These interactions offer the United States benefits including the soft power that arises from coordinating international efforts for peaceful purposes. OSAM activities were identified as potential areas for this collaboration.

Servicing

- Servicing is an important element of space-based infrastructure that can not only enable existing businesses but also create new businesses. The activities that servicing will enable—once servicing technologies and activities reach sufficient maturity—are expected to present a significant market pull in the future.

- There is growing interest in in-space transportation, whether transferring satellites to different orbits, moving an asset to its end destination once it has been assembled, or relocating raw materials for manufacturing. These early in-space transportation efforts will utilize the capabilities the satellite servicing community is currently developing and will continue to develop over the next decade or two. These servicing technologies may shape the initial infrastructure and architecture for future on-orbit activities.

Assembly

- Assembly offers significant value for science. A telescope with an aperture that is large enough to study exoplanets or other Earth-like planets cannot be launched from Earth intact—it can only be built in space. The capability provided by such a telescope is fundamental for scientific endeavors, and is a stated high priority from the science community. Assembly will also enable responses to failures after launch, enabling greater support for complicated missions. These assembly technologies will help entities move away from designs that require complicated and costly redundant systems.
- Attendees noted that there is no commercial market for science missions, but market considerations are not the only factors leading pursuits of space-based assembly. There can, however, be a market for the servicing of science assets, such as those used by the government.
- Assembly also offers value for exploration. It will enable persistent platforms (inhabited and uninhabited) through the assembly of large structures, and will allow infrastructures to be built for long-term missions without the restrictions imposed by launching from Earth (e.g., size or mass restraints due to single launch in a small fairing).[2]

Manufacturing

- Because space-based manufacturing can allow construction operations that are independent of Earth design, integration, and launch constraints, both government and commercial entities would be able to develop spacecraft whose size and capabilities can be built up over time.

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2 Although it was not mentioned in the discussion, another consideration is the volume/power/mass needed for an Earth-Mars roundtrip vehicle.

- Manufacturing could offer a useful opportunity for expanded commercialization of low Earth orbit (LEO). Initial commercial activity would benefit from a dedicated facility, which would not necessarily need to be crewed (e.g., a manufacturing station could be completely robotic).[3]
- While some in-space manufacturing endeavors will produce or support space assets such as spacecraft components or customized solid rocket motor propellant grains, there are additional uses for and applications of objects manufactured in space. These applications reach beyond the space sector and include medicine and terrestrial businesses.
  - Enabling these sectors to use in-space manufacturing will potentially require a lower-cost transportation system to deliver the materials to LEO and GEO and back to earth.
  - Sharing these capabilities with terrestrial endeavors could be supported by an in-space manufacturing facility in which interested entities could lease sections.

B. Business Cases

Servicing, Assembly, and Manufacturing

- Attendees largely agreed that on-orbit activities need more concrete business plans around the necessary sets of capabilities, especially for aspects that are difficult for commercial entities to pursue and achieve alone.

Servicing

- More information on and analysis of the business case for servicing is needed (e.g., there may be high value in the GEO realm, but this may not apply to LEO where satellites tend to be smaller, disposable, and less expensive). Demand is the primary aspect of developing the business case for servicing at this time.
- The business case for inspection (which is focused on GEO and viewed as profitable) will likely be the first to close.
- In addition to economic incentives, time can serve as the main metric for successful servicing business cases (e.g., speed of development, speed of services themselves, extension of mission, operation time lost from inoperable assets, etc.).

[3] Although they were not mentioned in the discussion, early trade studies indicate that perhaps an uncrewed facility helps to close the business case.

- The value of these activities is not just in replacing assets already on orbit—it is also in the innovation that comes as a result of newly-enabled capabilities.

Assembly

- The potential for profit in assembly is less clear in the near- to mid-term. Some attendees said the business cases do not close, while others insisted they do.[4]

Manufacturing

- No participant raised the issue of profitability for manufacturing. STPI's reports on the market case for a private space station and on-orbit manufacturing and assembly both discuss this topic.[5]

C. Funding

Servicing, Assembly, and Manufacturing

- Government subsidies, such as free transportation to the International Space Station, affect the market for space activities and services.[6] These subsidies change the business calculus for companies. Halting subsidies could be detrimental to market growth and technology development, especially for small companies and universities that cannot otherwise afford to conduct missions or research.
- When making IRAD investments, companies are estimating what the commercial and government markets for future technologies will look like.
- Entities (both governmental and private) need to continue to develop the technology for OSAM activities in order to improve understanding of the costs of these technologies and systems. These cost estimates will enable companies to pursue contracts for these services. Some activities and systems cannot currently be pursued because they are not affordable—not because of technological challenges.

Servicing

- Entities pursuing servicing technologies have many options for raising funds, including: government R&D funding, private venture capitalists, IRAD, and

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4 It is possible that the attendees speaking on this subject were thinking of different applications, but it is also possible they were hesitant to discuss proprietary information in the presence of competitors.

5 https://idalink.org/P8247 and https://idalink.org/P-8335

6 Previous STPI work on the market case for private space stations looked at this issue in more detail. https://www.ida.org/idamedia/Corporate/Files/Publications/STPIPubs/2017/P-8567.pdf

government commitments (e.g., guaranteed purchases).[7] The challenge is not technology development, but technology integration.

- Attendees noted that some investors accept a two or three-times return on investment, though typical venture capitalists will only be interested if the scale of return grows to 10 or 100 times the investment. If the activities offer a larger return, a greater pool of potential investors may be interested.

D. Coordination, Communication, and Standards

Servicing, Assembly, and Manufacturing

- While there is significant work underway preparing for on-orbit activities (some of which are scheduled for launch in the near-term), these efforts and projects are not well-coordinated or sufficiently communicated to a broad community of potential researchers, developers, investors, or customers.
- Current efforts face steep competition for limited funding. To combat this, attendees suggested that efforts to develop and test technologies should focus on cross-cutting experiments that will have overlap with the projects of many stakeholders.
- Because there is a finite amount of money in private IRAD, a system in which both governmental and commercial entities share information regarding what they are working on to avoid duplication and maintain strong technology transfer would be useful. This can also assist entities in identifying areas for collaboration.
  - There is concern that a large project forced to use an immature technology would present a “kiss of death” (e.g., the immature technology would increase the project’s risk so steeply that pursuing it over more traditional concepts would be untenable, and the project would not be able to continue).
  - With better coordination across agencies and partners, the technology causing the “kiss of death” could be matured elsewhere, mitigating the risk associated with its use.
- The sector and those involved would benefit greatly from a common understanding of terms and definitions for what operational capabilities are necessary for which services. Developing “Terms of Reference” could help. For

[7] One example, though in the launch sector (not OSAM), of where the government created demand was NASA’s Venture Class Launch Services program, where demand for launch services was created and thus spurred competitive product development. A similar strategy that could be applied to generating demand for servicing technologies.

example, “technology” is used too broadly when talking about OSAM, since it can refer to robotics, planning, scheduling, subsystems, systems, or anything in between.

- For future missions, a goal is to reach a level where entities are not designing new aspects or capabilities for every mission; some level of interoperability or standard would be preferred, though it may be difficult to establish.
- Organizations like the Consortium for Execution of Rendezvous and Servicing Operations (CONFERS) are strong initial points for setting industry standards (e.g., for rendezvous safety). If these standards are adopted worldwide, U.S. companies could help establish the norms of behavior and thus be well-prepared to serve international customers.
  - These standards should be developed and “pushed” by the private sector, not “pulled” or dictated by the government.
  - It may be possible to broaden the scope of CONFERS to include assembly and manufacturing, though creating separate parallel efforts in those areas may be more effective, given the different challenges each of the three fields faces regarding standards.
- Technologies for OSAM activities need to be generalizable (which will require moving away from the traditional model where technologies are made for a singular purpose). There needs to be an ecosystem or collection of tools that can be defined, standardized, and developed, with many stakeholders working together.
- OSAM is one area of the S&T Partnerships between NASA, NRO, and the Air Force, which see the value in both the technologies that will support these activities and the capabilities that will emerge from them. The common need for these capabilities has led these entities led to plan for a cooperative technology roadmap. Three S&T Partnership papers on in-space assembly will be presented in September 2018 at the AIAA SPACE Conference by NASA Langley personnel.

E. Verification and Validation

Servicing, Assembly, and Manufacturing

- Safety, certification, and validation processes are expected to be the main challenges to assembling and manufacturing satellites in space. In particular the safety constraints the ISS program imposes on external robotic activities could potentially add non-trivial design complexity.

- A certification process is needed so that objects assembled or made in space do not first need to be certified on the ground. Even if the current paradigm for testing and evaluation is updated, it will still require a follow-on system to approve the integration and use of components manufactured in space.
  - The conversation needs to move away from human safety issues (e.g., some restrictions prevent the testing of components at all due to a requirement for the system to be safe, meaning it cannot be tested).
  - Additionally, the system should accept that a process only needs to be tested once and, after initial testing, can be used freely.

F. Technology

Servicing, Assembly, and Manufacturing

- The transition from a system with a human in the loop to a fully autonomous system will be difficult, given potential risks and costs. The intermediate steps warrant attention.
- Most technologies will need to be demonstrated and perfected on smaller missions before they can be used for flagship or human-rated missions, and these missions will likely make use of many different technologies. Examples of these precursor technologies include relative navigation systems, robotics, refueling, and avionics.
- It was postulated that technologies from terrestrial robotics and automation could be more effectively and efficiently “spun-in” to OSAM. Expertise in these areas should be drawn in at a government level, not just a commercial level. Agencies across the government are already looking at artificial intelligence and machine learning, and attendees suggested that these entities should try to incorporate expertise from those and other areas in OSAM.

Servicing

- GEO is most likely a better place to start these activities than LEO: the population of vehicles that may benefit from the added cost of servicing is larger, and moving around within GEO is potentially less costly. However, technology maturation activities could take place in both LEO and GEO.[8]

[8] Although these were not mentioned in the discussion, some major robotic servicing missions have or are planned to occur in LEO, such as NASA’s Restore-L and Robotic Refueling Mission 3.

- As technology develops, it is expected that companies will try many different projects and approaches. A goal is for the servicer to have the same reliability as the spacecraft receiving the service.
- The processes for servicing an active satellite versus servicing a disabled or inactive object (which might be unstable or tumbling) are different.[9]
- A goal is to eliminate need for astronaut extravehicular activity (EVA) to perform a repair or upgrade.[10]

Manufacturing

- To achieve the full benefits of in-space manufacturing, many different kinds of manufacturing techniques beyond additive manufacturing (e.g., composite lay-ups, casting metals) should be adopted.
- For projects with large components where performance scales with size (e.g., apertures, antennas, solar panels), the main advantage of manufacturing is escaping the volume restriction imposed by launch.[11] The tooling to build these systems should not have to scale with the size of the final product.
- Both high quantity manufacturing (i.e., creating many small products) and high-mass manufacturing (i.e., creating products that face launch faring limitations) will be needed to offset the high initial costs needed to develop manufacturing capabilities.
- Although we do not expect to see complicated structures manufactured in space in the near term, attendees noted that initial efforts are expected to see a robot performing simple manufacturing actions, while a human manages the more complicated steps.
    - Human involvement moving forward might be based on certification (e.g., validating that an action would be better for humans than for robots).

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[9] Servicing in the GEO belt or 705 km Sun-synchronous orbit may drive higher reliability requirements than if the servicing were in less useful or less crowded orbits. It is also true that tumbling and uncontrollable satellites require greater maneuverability of a servicer during the capture phase, than if the client were 3-axis stable.

[10] This would also eliminate the human risk inherent in every EVA.

[11] Additionally, in-space manufacturing could help spacecraft design avoid the restrictions imposed by Earth's atmosphere –aluminum mirrors without coatings are not manufactured on Earth because aluminum oxide forms instantly in the presence of oxygen; this could not be the case in space. Without coatings, the reflectivity of mirrors increases, which is especially important for multi-reflection ultraviolet systems like spectrometers.

  - In-space manufacturing has the potential for commercialization. High quality optical fiber (e.g., ZBLAN) could capture a large share of the fiber market. Research in manufacturing ZBLAN is ongoing on ISS.

- Replacing components during long-duration space missions will be a challenge for systems produced through on-orbit manufacturing, though this capability would add significantly to the value proposition of the technology development.
- Today, components manufactured in space are primarily made of plastic polymers, but future missions will require metal and other materials.
- Recycling is an important manufacturing technology as well. Attendees discussed the utility of plastic, metal, and organics recycling (e.g., crewed deep space missions will have greater mass and volume restrictions; thus, recycling food, food packaging, and biological waste to manufacture other products would be particularly beneficial).
- Components will need to be designed to be repaired and replaced on a deep space mission. Objects will need to be manufactured and integrated on orbit.
- The strength of materials for on-orbit manufactured components will be a driver for some applications. For other applications, like large telescopes, a prime driver is the thermal stability of the manufactured component.
- In-situ resource utilization (ISRU) is expected to be a challenge. Shipping pieces to orbit and enabling systems to manufacture themselves will likely require a stepwise process. The government may be able to facilitate these steps (e.g., robotic servicing will enable assembly, assembly will enable manufacturing).
- It will be necessary to consider additive manufacturing with subtractive capabilities (e.g., one concern is about metal floating around ISS). When subtractive manufacturing is realized, it will allow for containing the material fragments on orbit; concepts for these capabilities have not been circulated yet. Getting through the certification process for an external manufacturing capability will be a challenge due to the potential of creating space debris.

G. Cultural

Servicing, Assembly, and Manufacturing

- From a mission manager’s perspective, it was noted that future spacecraft capable of being serviced, assembled, or manufactured in space can no longer be the same as those built in the past, and the same systems engineering tools used to develop those spacecraft cannot continue to be applied. Future processes and teams need to consider alternative scenario planning, accept more risk to mature these technologies faster, document lessons learned more effectively, and think from the beginning of the lifecycle about how a spacecraft would be different with new on-orbit capabilities or options.

  - For example, “software-defined radio” has changed some ways that spacecraft engineers think about designing elements of on-orbit hardware.
  - Thinking more along the lines of “firmware-defined spacecraft” that are flexible, reconfigurable, upgradeable, or otherwise changeable in ways that can capture previously unarticulated value after launch may be a better way to frame the design process.

- Integrating on-orbit manufacturing and related technologies into government systems and missions will require a culture change. For example, if there is an issue in part of NASA’s environmental control and life support system (ECLSS) in the ISS, the entire system is removed; the ECLSS project team is struggling to discuss incorporating additive manufacturing as a solution. It is also expected that the cultural inertia in government agencies against servicing will take time to change.
- The perception that servicing technologies are challenging or controversial will be just as debilitating for the development of these capabilities as restrictive regulations.
- Industry also faces challenges when working with the government, specifically DOD. The lack of a process for industry interactions regarding satellites and satellite-related technologies, and especially emerging technologies, such as on-orbit servicing, presents a regulatory and policy barrier.
  - The Air Force is involved in on-going conversations regarding these new technologies and recognizes that the conversation needs to switch from “why are you in my office” to “how do we integrate this process.”
  - Some government entities do not accept the increasing difficulty of hiding satellite activities in space from potential adversaries as non-U.S. space capabilities continue to improve.

H. Policy and Regulations

Overall

- Some current policies that restrict new and emerging technologies may restrict servicing activities (i.e., there is concern that the same mistakes will be made with regulation of space remote sensing that were made with Earth remote sensing, and some argue that sensors used for close-distance remote surveying should not be subject to the same regulations governing sensors with the capability to do long-distance satellite surveillance).

- Some industry representatives indicated that policy is not a barrier in general; indeed, some policies enable companies to pursue activities they believe will be commercially beneficial.
- Concern was expressed that the government is losing the ability to respond quickly as technologies evolve and as adversaries change technical and policy directions.
- Any activity in space involving close proximity between assets presents real and perceived threats: an entity may be concerned about the capabilities of the approaching asset.
- To encourage sustainable behavior in space, a system could be implemented where an entity pays a deposit when launching a satellite and receives the deposit back when the debris has been removed successfully. These behavioral standards could set a framework for OSAM activities while protecting the orbits these activities will require.

Space Licensing

- Attendees agreed that the regulatory environment should encourage investment and commercial operations. The process should emphasize efficiency, affordability, and transparency.
- If the U.S. does not address the current issues in its regulatory system, it may cede leadership to other countries that will then set norms of behavior.
  - Other countries (e.g., UK) are reviewing their own regulatory systems to make their nations more appealing for space companies to locate.
  - Although other nations expect the U.S. to lead, the government has not made the role of international partners clear in U.S. plans moving forward.
- Because the barriers to approval in the U.S. licensing process are perceived to be high, interested nontraditional entities might be discouraged (e.g., they may stop pursuing the technology all together, or they may move their enterprise overseas). While larger companies can likely afford to follow the process, the current system will adversely affect smaller and newer entities.
  - It will be important to ensure that barriers to entry in space and OSAM activities specifically are not so large that small companies cannot engage (e.g., due to limited personnel, or lack of familiarity and experience with the process).
  - If U.S. companies are not able to lead with technologies and practices, foreign entities (private and public) may take a greater role in setting norms of behavior.

- The government often uses stretch or temporary solutions, and the current licensing process lacks established procedures (nobody owns it). Whichever entity is given regulatory responsibility needs the authority to be doing the licensing.
  - The ad hoc process involving FAA and State needs to be addressed; this is especially relevant as insurers and investors look for dependable responses, and industry needs regulatory reassurance. Although the AST has managed the process well under its limitations, it does not have full authority and has been unable to treat licenses as precedent, contributing to an unclear regulatory environment for future applicants.
  - There is need for greater transparency for license applicants in the interagency process for space-related licensing.
- The "one stop shop" intended to be created by Space Policy Directive (SPD) 2 is an overstatement and perhaps an aspiration—the Department of Commerce's process will not include the FCC, FAA's launch licensing, or the proposed payload review process.

Export Controls

- Export controls can limit innovation. The currently proposed legislation indicates the potential initiation of a third list (a new control list, in addition to the United States Munitions List and Commerce Control List), which is contradictory to the sentiment of reducing the unnecessary regulatory burden as outlined in SPD 2.
  - It would be useful to avoid legislation that expands export control and Committee on Foreign Investment in the United States (CFIUS) control simultaneously.
  - Sentiment was expressed that if export controls were reformed, it would mitigate the need for CFIUS reform.
- The U.S. cannot and should not pursue OSAM activities alone. However, dual-use technology in this area is likely to make international collaboration challenging (possibly more difficult than collaboration for the ISS, which was given specific export exceptions to allow and support international collaboration). Sharing interface standards may not be sufficient; reform of International Traffic in Arms Regulations (ITAR) and other export control regulations may be necessary to allow and encourage these collaborations.

Space Law

- Attendees did not believe the Outer Space Treaty needs any major changes, and claimed the current Treaty frameworks are adequate.
- Undertaking OSAM activities will necessitate a reorganization of the framework for approaching space. All licensing and related processes presume launch from Earth. If this changes (e.g., a spacecraft is manufactured and then maneuvered in space), it will affect the categorizations and models for numbering, licensing, liability, etc.
- Because most rules were written to protect people on Earth during launch, liability in space remains uncertain.
  - The maneuverability of satellites and possible on-orbit manufacturing necessitates a re-analysis of the regime and an international conversation regarding the domain.
  - Some discussion of behavior in space could be mitigated by a set of notifications regarding the prescribed and activities of any object in space (similar to a flight plan).
- In the future, space law may transition from a launching state paradigm to one where it is possible to identify who is responsible for pieces of debris that affect other satellites, or which entity made a decision that created liability, and use contracting mechanisms to collect penalties for damages.
- The Outer Space Treaty outlines broad principles but does not clarify specifics; some aspects could be redefined. There are some questions regarding whether recent and potential future activities or processes contradict the treaty (e.g., licensing, rescue/return); if these are deemed to be augmentations but not contradictions, they have not undermined the Treaty or its principles. It offers plenty of room for interpretation, and nothing has been well-tested in court. For example, the Treaty refers to the “appropriate state,” not the “launching state.”
- Rather than opening the Treaty to amendment or renegotiation, the U.S. should begin by engaging in bilateral and multilateral discussions with launching states and spacefaring nations; once there is agreement, norms of behavior can be brought to the United Nations Committee on the Peaceful Uses of Outer Space.
- The U.S. can take a lead moving forward: establish a system for the U.S., set norms, set international standards, and have bilateral conversations first with allies, then with other nations, to disseminate that norm. It would be crucial that the U.S. is transparent in its discussions about its activities and reasoning throughout this process.

Salvage Rights

- Because, as per the Outer Space Treaty, nations retain ownership of everything they put in space, current space law does not authorize the salvage or recycling of materials. This is a potential area of change in space law, though it is not expected that nations would be willing to give up ownership of their own debris in orbit.
- A conversation regarding salvage would be useful from both regulatory and industry perspectives. A policy statement would be key for salvage rights and could unleash industry to be more creative.
- Potential applications of OSAM activities include transporting materials to orbits where they will be used; removing debris to clear an orbit for use; and reusing materials as part of a commercial architecture. It is possible that in the future, with government permission and under contract, an entity would be able to collect space objects if they were willing to undertake the associated liability issues; this process would be a useful area for future discussion.
- Industry groups are looking to incrementally manage the debris in space. For example, an operator might pay a company to clear material out of a desired orbit. The objects could simply be moved, but harvesting and using these objects for another application could be a business option as well.

I. OSAM Roadmap or Strategy

- The usefulness of a whole-of-government roadmap and strategy was discussed. Some think that such a document would put constraints on the OSAM enterprise, reducing the flexibility for pathways and options in the future. While some attendees noted that a roadmap might be useful for advocacy in Congress, others said it could be used against them by the same people if the pathways for OSAM changed.
  - Skepticism was expressed about around roadmaps in general, especially for substantial projects.
  - A roadmap or strategic plan may be useless (and possibly a distraction) if it is not supported by schedules or funding allocations. Even with this support, a roadmap that is too detailed may stifle innovation or restrict development, and thus may not be effective.
  - Splitting the milestones into more manageable and tangible pieces and spreading them across many missions may help with buy-in on the legislative side.

  - It may be helpful to move away from the “roadmap” and “strategy” terminology, and instead talk more about an “integrated plan” as a loose pathway forward. Within this, a strategic plan may be useful to clarify regulatory requirements and authorities for OSAM activities.
  - Whatever is put forward may be better if it is informative, rather than prescriptive.
  - One participant noted the potentially limited usefulness of strategic plans by pointing out that NASA’s technology roadmaps are no longer the guiding principles for space endeavors, and they are not referred to often or touted in Congress.
- It was stated that it would be useful if a Space Policy Directive or other National Space Council document asserted that OSAM is an issue of critical importance going forward; this would state, at the Presidential or Vice Presidential level, that OSAM is important to U.S. leadership in space. This policy could include calling for experiments or demonstrations, reform of export controls (specifically ITAR), a broader interpretation of the Outer Space Treaty, and increased engagement with aerospace industry associations.

J. Roles of Government

Overall

- Government should consider the benefits to and interests of the public, and not make infrastructure decisions solely based on narrow business cases. Government cannot afford to build expensive systems that are not serviceable.
- Government should fulfill its mission, using whatever technology is necessary (e.g., on-orbit servicing should not be pursued simply for the sake of on-orbit servicing; rather, the developing technologies should be utilized and integrated if they support and further a government use). The government should go to industry to develop those capabilities. Commercial entities will fill in gaps if the government articulates specific needs. These efforts could be supported if the government (NASA specifically) established a vision and mission goal.
- The government could help push the technology by planning a large project that needs OSAM (though it was noted that a project would need to have achieved sufficient progress before being ready for OSAM technologies). However, the alternative was also suggested, where instead of the government pushing along the technology, it considers technology that has been sufficiently matured to be pulled.

  - It is easier to establish policy that is a declaration of victory, in that the U.S. is no longer afraid and is ready to incorporate these technologies into its missions.
  - This might require significant cultural changes. A goal would be to foster innovation rather than prescribing capabilities.
- Agencies need to collaborate and determine which capabilities will be necessary moving forward; they can then cooperate to pursue the most common and high-priority needs, rather than their niche, single-use cases.
- Changes in administrations that affect NASA plans and goals negatively affect long-term capability development. One option is to separate on-orbit activities into segments that can be accomplished in a single administration; these capabilities then can be handed off to the next leadership team, which will decide if the mission should continue or change direction. A well-articulated value proposition hiding beneath a major, more politically volatile, flagship human campaign could help prevent a complete reset.
- NASA should help industry determine which advances will have the greatest payoffs while allowing industry to build the vehicles; this would be similar to a relationship previously maintained with industry by NACA.
  - For example, governments worked closely with industry on developing composites; rather than simply replacing technology and aspects that already existed, industry was instead able to create new applications that were not possible before.
  - NASA needs to consider working to put OSAM technologies together as well as handing them off to industry.
- NASA can have a global impact: its brand includes servicing, launch is enabling technical ambition, and NASA is investing in a variety of technologies.

Infrastructure

- The proper role of government in OSAM activities moving forward still needs to be determined, especially regarding its support of industry efforts (e.g., would the commercial sector want a spaceport asset? Should the government be the primary funder of in-space infrastructure to promote these activities?).
- It would be useful to put in place government programs that provide an ecological niche in which OSAM can thrive. To start, NASA and other government agencies could identify ways in which it makes sense to incorporate these technologies at a mission level, or provide incentives for technologies to be adopted where they can be (e.g., refueling valves). Identifying these needs

and uses will create incentives for private companies to offer those services, even in the absence of other commercial markets. Having government as a first customer can help drive more customers (NASA's Commercial Orbital Transportation Services [COTS] program could be a model).

- The government can provide the infrastructure for the private sector to use in technology experiments to support maturation of these technologies, easing the burden of proof (i.e., it is difficult to physically test something without building it).
  - The government can provide more rideshare and secondary payload opportunities for technology experiments and demonstrations.
  - An uninhabited platform where assets can be attached is significantly more attractive than the ISS due to the Station's safety issues and hurdles. The government could offer something intentionally built for science and external demonstration.
- The ISS could be used for the maturation of technology. However, the potential to end direct funding to ISS in 2025 presents some challenges (e.g., how much money should the government spend on a space station for technology maturation alone? If the ISS were de-orbited, what would be the next platform?).
  - The ISS could be best used if barriers to entry for space activities were lowered, allowing more groups to test their technologies and prove their business cases.
  - The ISS poses some restrictions for on-orbit manufacturing (e.g., for manufacturing metal, the express racks only have a few hundred watts of power; the temperature of the system's front panel needs to be better controlled).
  - A private station in LEO could be useful for this maturation as it may be more flexible than a station owned and operated by the government. This would also help lower the cost barrier for conducting these activities.

Cultural

- Several participants noted that a government culture change regarding emerging technologies, space, and on-orbit activities is needed. The expectation for space missions needs to move away from single-launch, single-use spacecraft.
- Government and commercial entities could put incentives in place for mission managers to incorporate OSAM activities into their programs, allowing them to avoid potential downsides (e.g., high risk) and change the culture of the systems engineering lifecycle.

  - The system should encourage project managers to consider designs that incorporate OSAM during the proposal and review process, not just eliminate these elements because the risk is higher or cost is harder to calculate when compared to traditional systems. For example, industry was slow to propose designs with composites due to concern that the risk involved would kill the proposal prematurely.
  - Additional integration of servicing-enabling technologies could be supported through a policy that makes satellites upgradeable without holding the project manager accountable for the costs of the upgrades. For example, the government could mandate that all government satellites use cooperative servicing valves to encourage and support future servicing missions (the cost of implementing this for all satellites is in the range of a few million dollars).
- Development, regulation, and approval of OSAM activities would benefit if the community overcame the view that there are different rules for missions of government exploration and use versus missions for commercial profit-making; this would enable commercial systems to continue to develop as well as be used by the government.

K. Roles of Industry

Overall Roles

- Beyond technology development, the private sector can explore technology infusion and the demand side of the OSAM equation, including price points, business cases, potential cost savings, and other information to help sell the idea of OSAM, not just develop the technology.
  - Industry could help the government understand that OSAM techniques can be effective at reducing cost and risk, improving program schedules, and enabling government to form partnerships; this could support numerous missions that are not currently possible.
  - Industry could examine both sides of the equation—cost and profit—and encourage entities to pursue activities involving OSAM (e.g., emphasize that serviceability does not need to be incredibly expensive, as it was with Hubble). Low mass valves and rendezvous decals may help initiate this effort.
- Industry could also emphasize the additional benefits on the ground from using modular and serviceable systems (e.g., lower integration and testing costs and challenges).

- Industry can help change cultural norms with customers, such as by encouraging all involved entities to default to using enabling elements such as cooperative servicing valves.
  - Discussions of OSAM technologies with customers could help identify other innovative solutions to challenges regarding design or value propositions.
  - An example was discussed where one-on-one servicing agreements were not selling, but the involved parties agreed on fleet management as a useful solution as a result of industry conversations with the customer.
- Industry could determine which projects have commercial potential and which would have NASA as the sole customer.
  - Industry could guide government toward assuming the risk for technology development rather than pursuing these through public-private partnerships. These decisions influence where companies allocate IRAD money.
  - Determining how much IRAD a company should spend on developing certain technologies for specific programs when that technology is applicable in other areas versus how much the customer (e.g. the government) should pay for that development should be part of a two-way discussion regarding contracting mechanisms.
- It will be important for several key issues in OSAM, such as defining and promoting standards, that industry trade associations collaborate and communicate with the government and other stakeholders. The influence of these associations could affect many aspects of OSAM activities such as cryogenic fluids, force, and transferring power. It was suggested that any development of standards not include company IP, but rather be open source and openly accessible.
  - Forums could be established to create pathways from industry to government. The government would prefer to interface with industry associations rather than single companies (to avoid many issues, including appearing biased by listening only to a few companies).
  - Industry organizations could lobby to protect spectrum allocation moving forward.

International

- Industry needs to join the international conversation alongside the State Department and work together to establish norms of behavior, general rules of the road, etc. to ensure commercial interests are considered and commercial experience is taken into account.

- It will be increasingly important for industry to be involved in resolving disputes in any international system. An effort is needed to identify ways or ideas for motivating industry to become and remain involved.

L. Next Steps

At the conclusion of the roundtable, attendees discussed next steps to resolve challenges in and to better support on-orbit servicing, assembly, and manufacturing in the United States. In addition to these next steps, workshop attendees expressed interest in meeting again to continue the dialogue.

4. STPI Assessment and Next Steps in OSAM Activities

In the course of analyzing the questionnaire results and summarizing the discussions, STPI developed a data-driven, bottom-up model for systematically grouping current programs as well as the discussion topics, challenges, drivers, pathways, and recommendations offered by attendees to help frame future work in OSAM. The model loosely takes the shape of a horseshoe, or "incomplete wheel," a near-circle with one section cut out, allowing for numerous connections throughout the wheel. The eight sections of the wheel are not strict categories, as some topics, solutions, or projects may bleed across the edges or have foci in multiple areas. The categories, starting from the top left and working clockwise, are:

- **Policy:** relating to national or agency policy, including overall funding efforts, overarching strategy, and interagency priorities.
- **Program:** relating to agency design culture, agency funding decisions, concept selection methods, and coordination among multiple missions.
- **System:** relating to individual missions, spacecraft, infrastructure, larger subsystems, launch, and other supporting technologies not strictly conducting OSAM activities.
- **Technology:** relating to subsystem components and technologies responsible for OSAM activities, such as robotic arms, welding systems, and additive manufacturing plants.
- **Verification and Validation:** relating to ensuring technologies conducting OSAM activities are consistent, measureable, and communicated to customers.
- **Standards:** relating to design standards for individual parts, best practices, procedures for standardization, and norms of behavior.
- **Regulations:** relating to licensing, enforcement, best practices, penalties, liability, property protection, and codified laws.
- **Collaboration:** relating to all the other sections, serving as a nexus that includes coordination between government and industry, international dialogues, technology sharing, and outstanding treaty questions.

Categories near the top of the wheel focus on broader issues, while categories near the bottom are narrower in scope. Categories on the left focus more on policy, law, and partnerships, whereas categories on the right consider systems, technology, and hardware. Although the Collaboration category is graphically placed on the center left, it contains elements across both axes and serves as a catch-all, not just the link between high-level policy and detailed regulations; hence the dotted instead of solid line. Figure 1 shows this model along with descriptive axes and rough ideas of where certain subfields might fall along the circle.

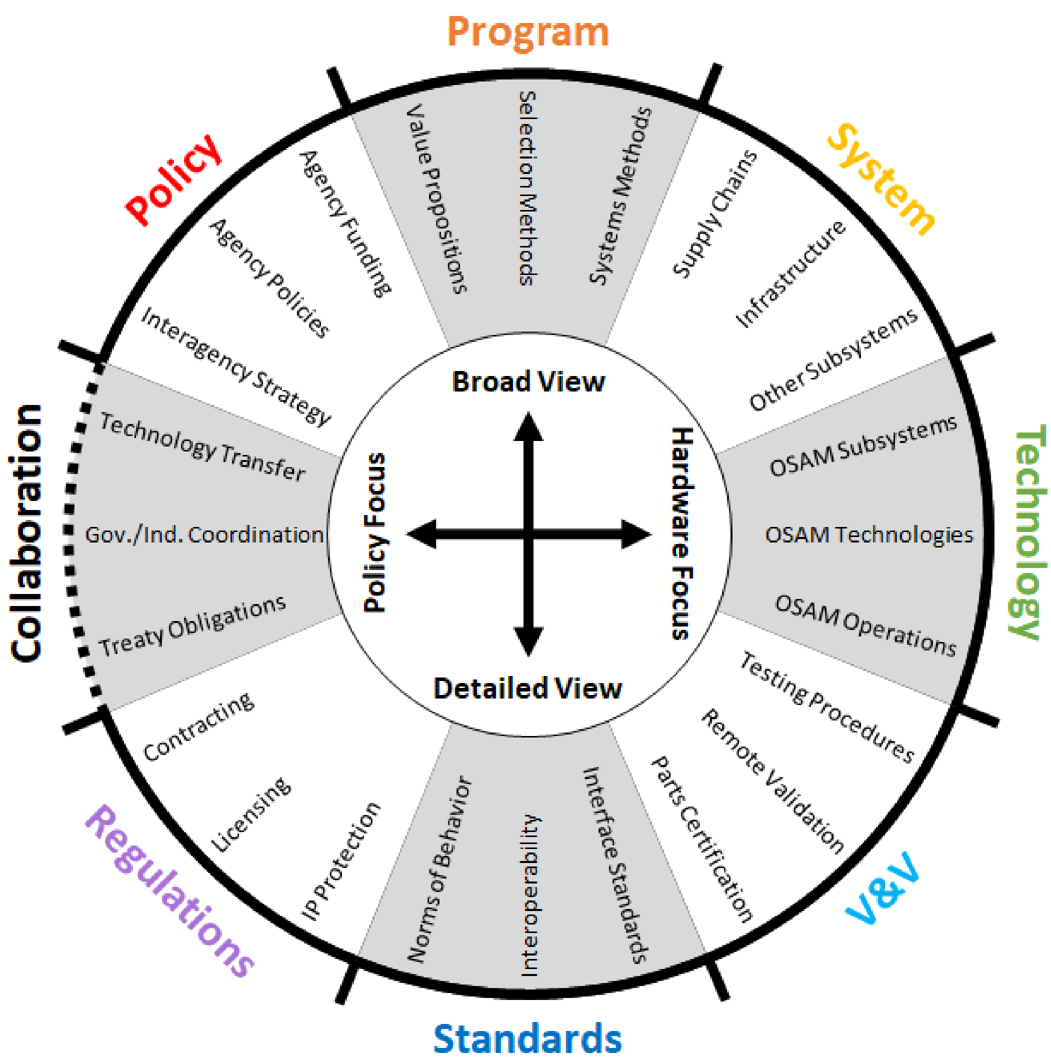

Figure 1: Open Wheel Model of OSAM activities

Next, STPI revisited questions 5 through 10 of the pre-roundtable questionnaire (see Appendix D). In those six questions, questionnaire respondents identified 33 challenges, 26 drivers, and 28 pathways forward, and these were plotted within the model. Figure 2 visually displays the challenges using the model, Figure 3 shows the drivers, and Figure 4 shows the paths forward, with each successive figure retaining the graphical elements of the previous one. Each element was plotted approximately where it would fall on the spectrum, though some elements naturally span several topics, and elements should not be considered discrete points but rather approximate positions.

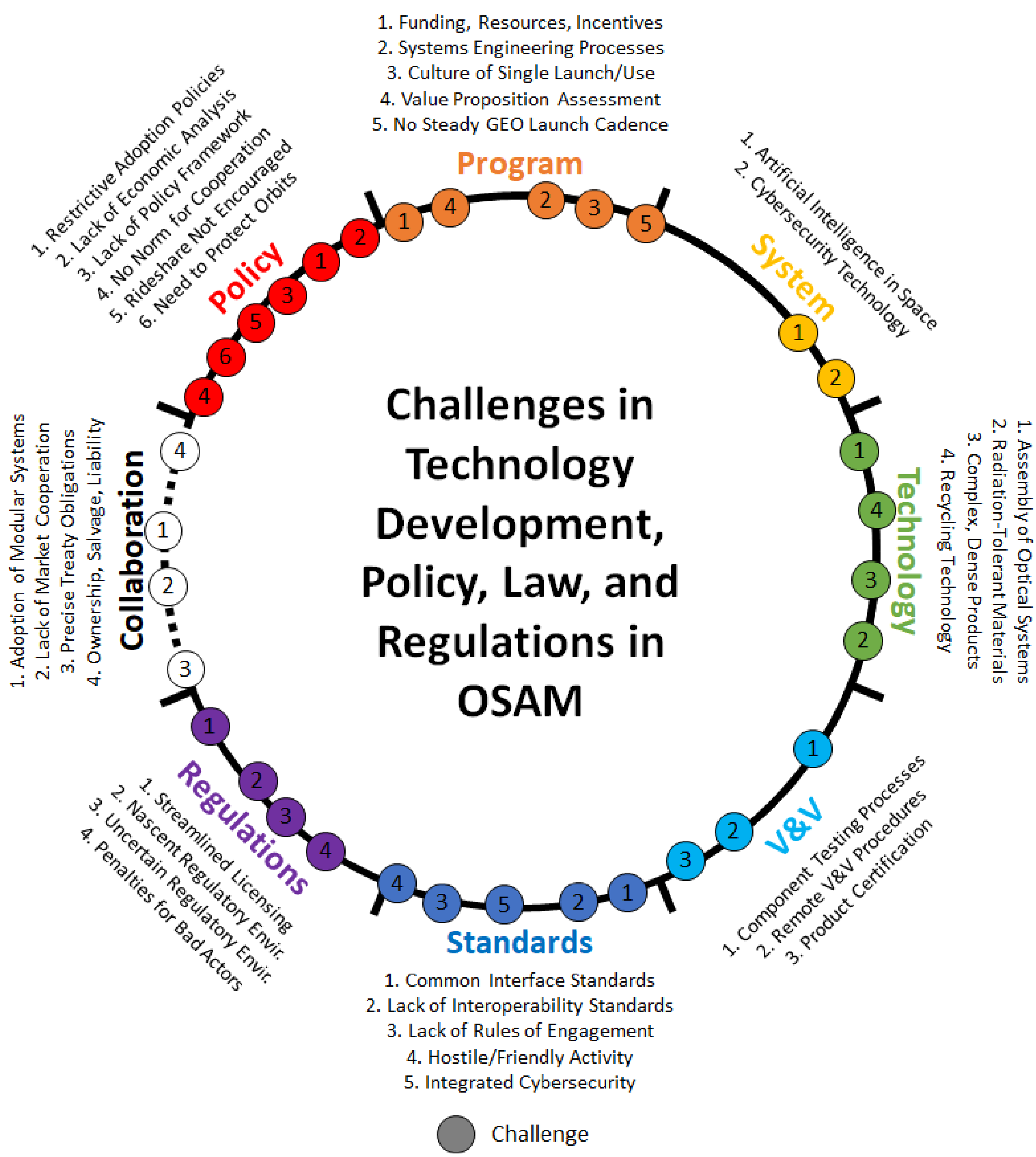

Figure 2: Mapping of challenges that were identified by questionnaire respondents onto the open wheel model

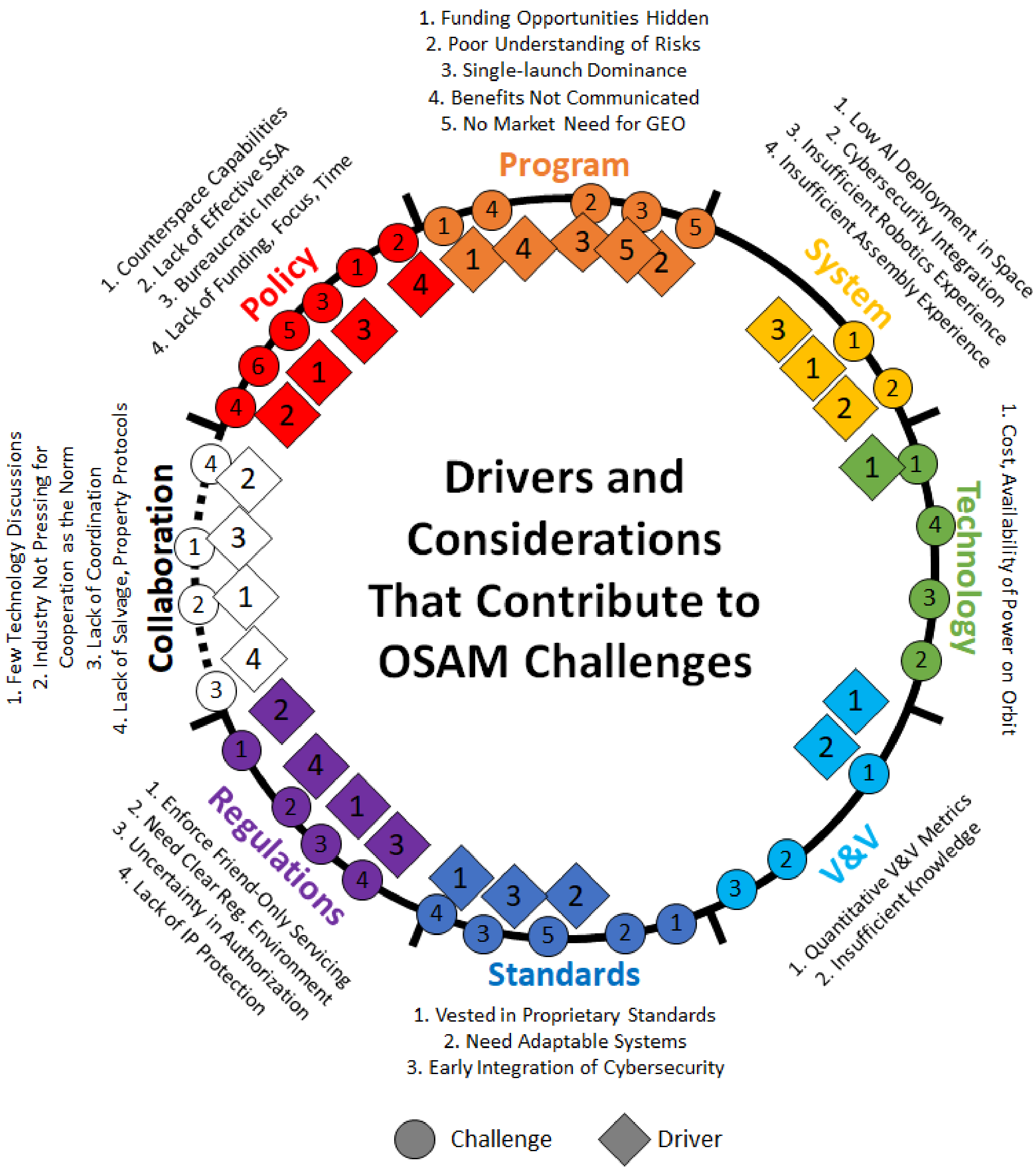

Figure 3: Mapping of drivers that were identified by questionnaire respondents onto the open wheel model, along with previously mapped challenges

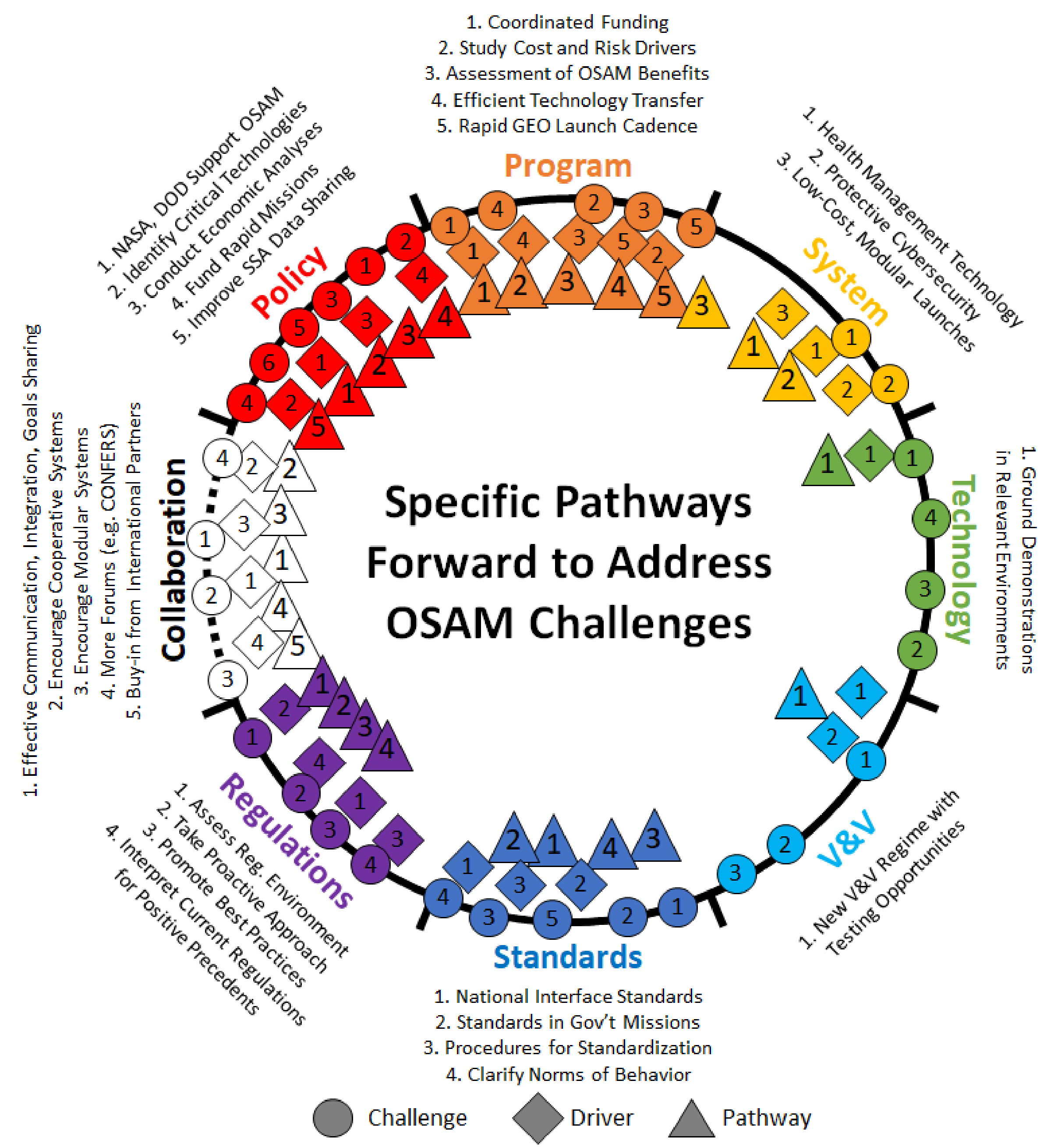

Figure 4: Mapping of pathways forward that were identified by questionnaire respondents onto the open wheel model, along with previously mapped challenges and drivers

A. Current Programs in OSAM

STPI examined the existing and planned OSAM programs (Table 1). Of these 22 programs, half (11) of them are focused on servicing or technologies that will help enable servicing, and the ones that are focused on assembly and manufacturing tend to be less mature and further from launch than the others. More than half (13) are government-led, with seven U.S. commercial programs and two international programs. Three of these are NASA missions with broader focus than OSAM, seven are technology demonstration missions, seven are meant to be the start of a service in space, three are focused on developing standards, and two are paper studies.

Table 1: Existing or planned OSAM programs

Name	Lead Organization	Lead Type	Project Type	Activity
CLPS	NASA Robotic	Government	Service	Enabling Technology
Insuresat	Chandah	Commercial	Service	Servicing
Raven	NASA Robotic	Government	Tech Demo	Servicing
OSIRIS-REx	NASA Robotic	Government	Science	Servicing
PODS	DARPA	Commercial	Service	Enabling Technology
RRM3	NASA Robotic	Government	Tech Demo	Servicing
RemoveDEBRIS	Surrey	International	Tech Demo	Servicing
MEV	Orbital ATK	Commercial	Service	Servicing
Space Drones	Effective Space	International	Service	Servicing
Restore-L	NASA Robotic	Government	Service	Servicing
CONFERS	DARPA	Government	Standards	Servicing
DSIS	NASA Crewed	Government	Standards	Assembly
RSGS	DARPA	Government	Service	Servicing
IDS	NASA Crewed	Government	Standards	Assembly (Station)
ISS	NASA Crewed	Government	Mission	Assembly (Station)
LOP-G	NASA Crewed	Government	Mission	Assembly (Station)
STMD TP: Dragonfly	SSL	Commercial	Tech Demo	Assembly
STMD TP: Archinaut	Made In Space	Commercial	Tech Demo	Manufacturing
STMD TP: CIRAS	Orbital ATK	Commercial	Tech Demo	Assembly, Manufacturing
S&T Partnerships	NASA Robotic	Government	Study	Assembly
SSPD Tech Transfer	NASA Robotic	Government	Study	Servicing
Vulcan	Made in Space	Commercial	Tech Demo	Manufacturing

STPI mapped these programs to the open wheel model in Figure 5. Figure 6 shows that same mapping along with a mapping of the challenges that were identified in the pre-roundtable questionnaire (seen in Figure 2).

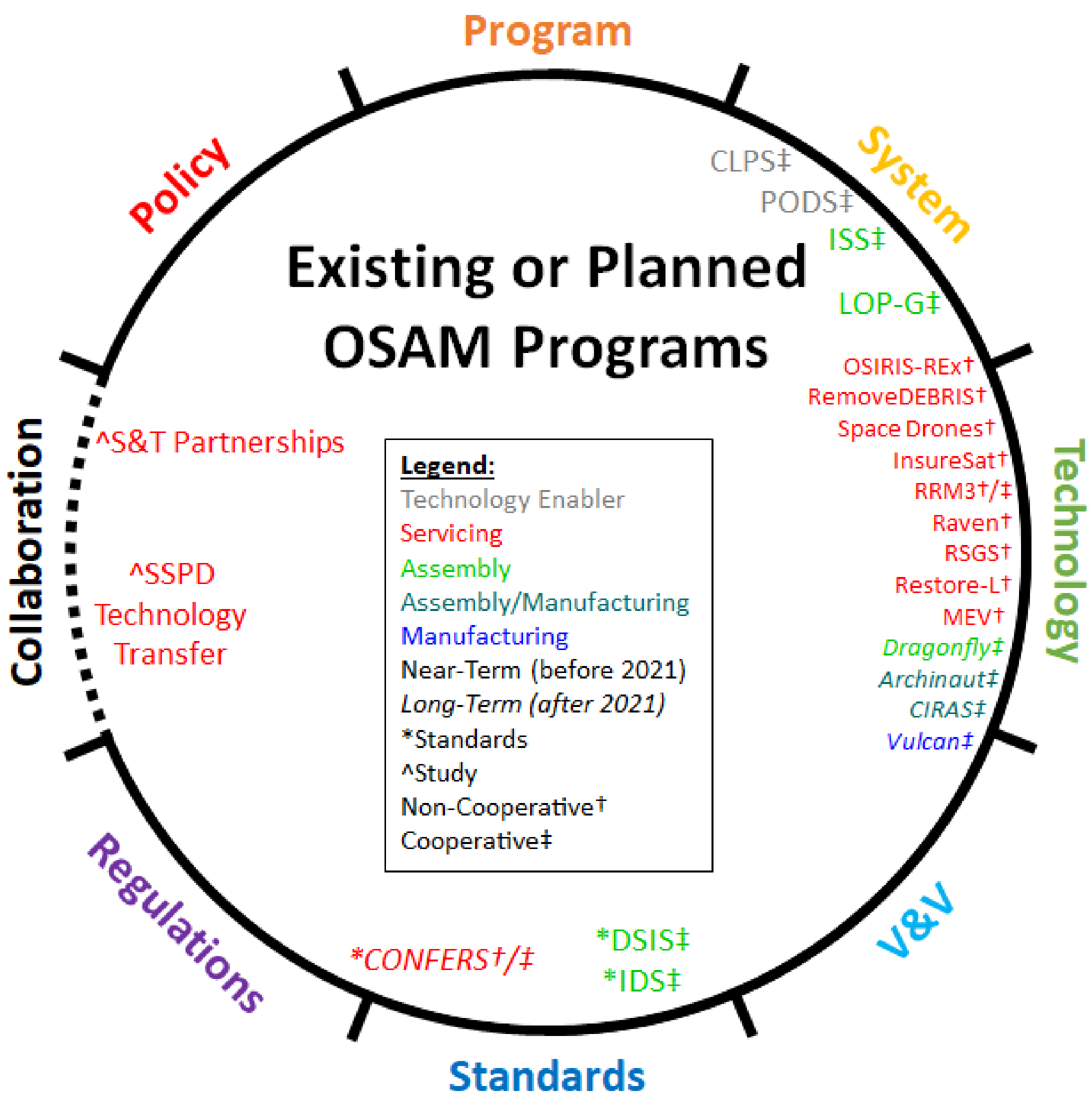

Figure 5: Existing or planned programs in OSAM mapped on the open wheel model, sorted by activity and type

Figure 6: Existing or planned programs in OSAM mapped along with challenges identified in the questionnaire (from Figure 2) on the open wheel model

Given the mapping of the challenges that questionnaire respondents identified compared to the mapping of existing activities as shown in Figure 6, as well as what was discussed at the roundtable event, it is clear that more can be done to ensure the United States remains a world leader and advance the state of the art in on-orbit servicing, assembly, and manufacturing, especially with regards to policy, program, verification and validation, and regulations challenges.

B. STPI Policy Options

Based on the analysis of the questionnaire results and recommendations made at the roundtable discussions, as well as a review of current programs, STPI produced the following policy options that OSTP could pursue to help ensure that the United States remains the world leader in these important, emerging space activities.

1. **Conduct analyses to assess the value propositions of OSAM and identify if there are missions where OSAM approaches yield scientific, economic, or other benefits.** Benefits to be considered include both financial profitability for commercial entities and increased payload performance for national security and science missions. The assessment will differ for servicing, assembly and manufacturing; and the assessment may be useful for all sectors, public and private. The results of the analyses should be shared with government, industry, and public stakeholders to encourage new thinking in mission design and operations.
2. **Revisit space systems concept selection methodologies to better articulate and characterize the value and risk from non-traditional space mission concepts.** Adopting new methods can help break the traditional systems engineering lifecycle, which has broader implications beyond only OSAM. Specific practices to revisit include NASA's Systems Engineering Handbook and methods used by concurrent design engineering studios like Team X.
3. **If these value propositions prove that OSAM can deliver value, support government entities (e.g., NASA, USAF) to develop space systems practices and policies that will encourage the adoption of OSAM approaches.** Examples include activities, programs, and initiatives that incentivize mission managers to select OSAM technologies or accept added risks and costs associated with OSAM parts; challenge approaches used to build spacecraft in space; and apply OSAM thinking to future missions.
4. **Encourage consideration of technologies and approaches that can be leveraged from terrestrial sectors to benefit OSAM and future space activities**. Examples include robotics, automation, and AI. This expertise should be drawn in at both the government and private sector levels to inform strategies and decision-making. OSTP can bring more AI research expertise on board in future OSAM discussions.
5. **Ensure the availability of on-orbit platforms for the development of OSAM technologies and approaches.** This can begin on the ISS (e.g., as RRM 1, 2, 3 and Raven were) and then continue with a robotic platform for the post-ISS era that can be used to experiment with, demonstrate, and rapidly evolve OSAM technologies and activities.
6. **Promote, and enable rideshare technology experiments on government missions.** More launch opportunities and a faster launch cadence will quicken

the pace of technology development and adoption in both government and commercial missions.

7. **Review, clarify, and, where possible, simplify and streamline all licensing policies and regulations relevant to OSAM activities.** Examples of where attention is particularly needed include: Earth observation licenses for spacecraft conducting nearby satellite inspections; communications licenses for optical communications systems; waivers on maximum orbital lifetimes for persistent platforms or other vehicles that are refreshable; and "launch" licenses for spacecraft that are "born" in space rather than launched from Earth.
8. **Using transparency and confidence building measures, facilitate the development of standards and norms of behavior for OSAM (which may differ considerably between servicing, assembly, and manufacturing) with the private sector and aerospace industry associations.** These should include: minimum safety standards for rendezvous and proximity operations for servicing; certification for systems integrated and tested in space; and verification and validation procedures for parts assembled or manufactured on orbit.
9. **Encourage international collaboration across OSAM activities. Potential areas include: technology development and adoption; technology sharing and export control; standards and practices; salvage rights; and debris mitigation.** Bilateral agreements and smart contracting mechanisms can be used to avoid potential violations of the Outer Space Treaty.
10. **Develop a coordinated approach, though not a formal interagency strategy, to better align government and industry efforts in OSAM.** The approach should recognize the broad set of stakeholders, funding sources, timelines, success metrics, and end goals. It should integrate technology development endeavors as well as the establishment of standards and practices for servicing, assembly, and manufacturing. It is critical that this strategy is backed with schedule commitments and appropriate funding levels to complete the actions therein.

Figure 7 shows STPI's policy options mapped on the Open Wheel model showing that these policy options span a wide range of categories. Figure 8 shows the policy options mapped to the specific challenges that were identified in the pre-roundtable questionnaire that they address, showing that these policy options individually help address more than one challenge each and collectively address all identified challenges. These policy options also address other challenges that were not identified in the questionnaire but were discussed in the roundtable.

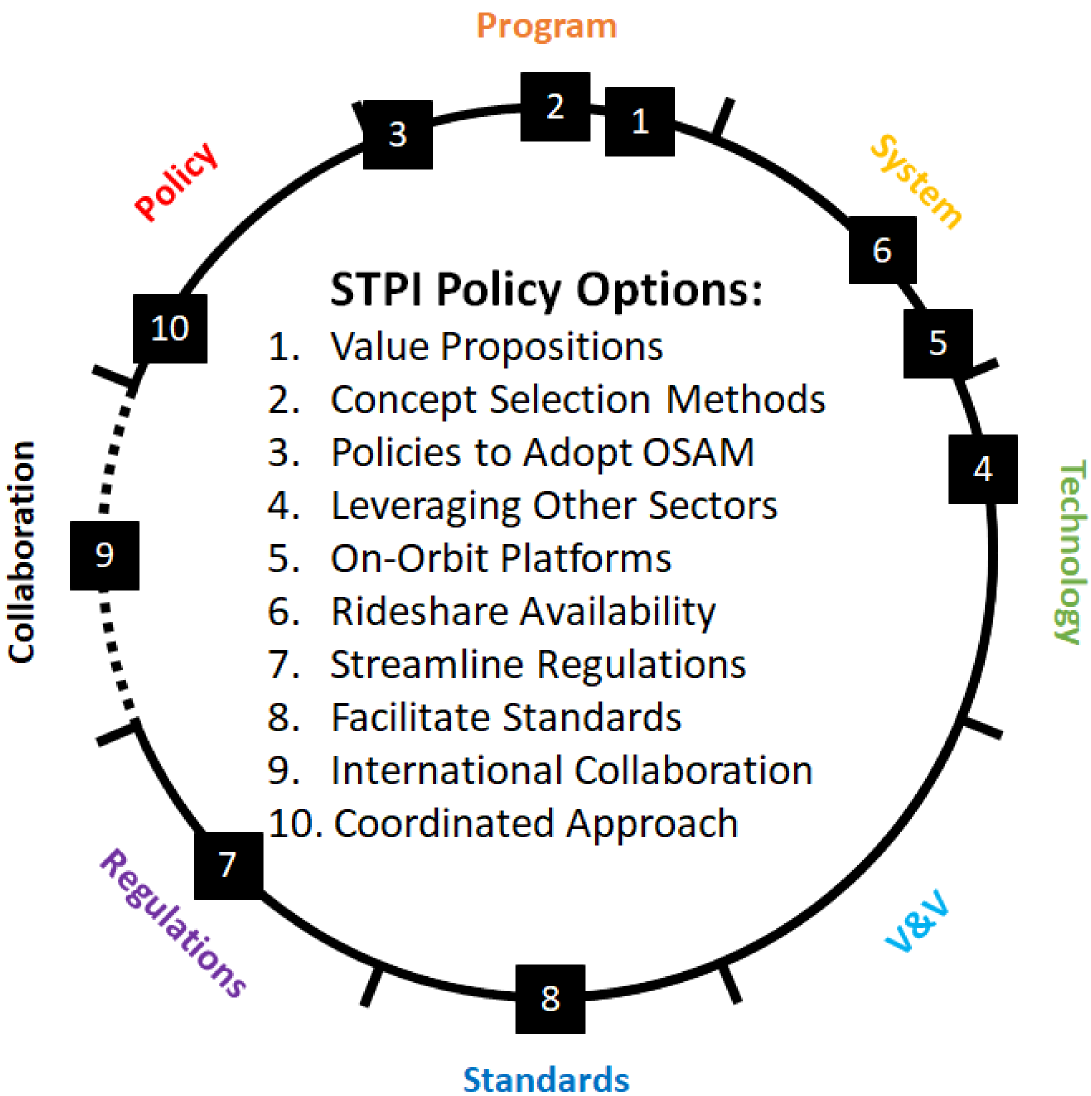

Figure 7: Policy options mapped on model

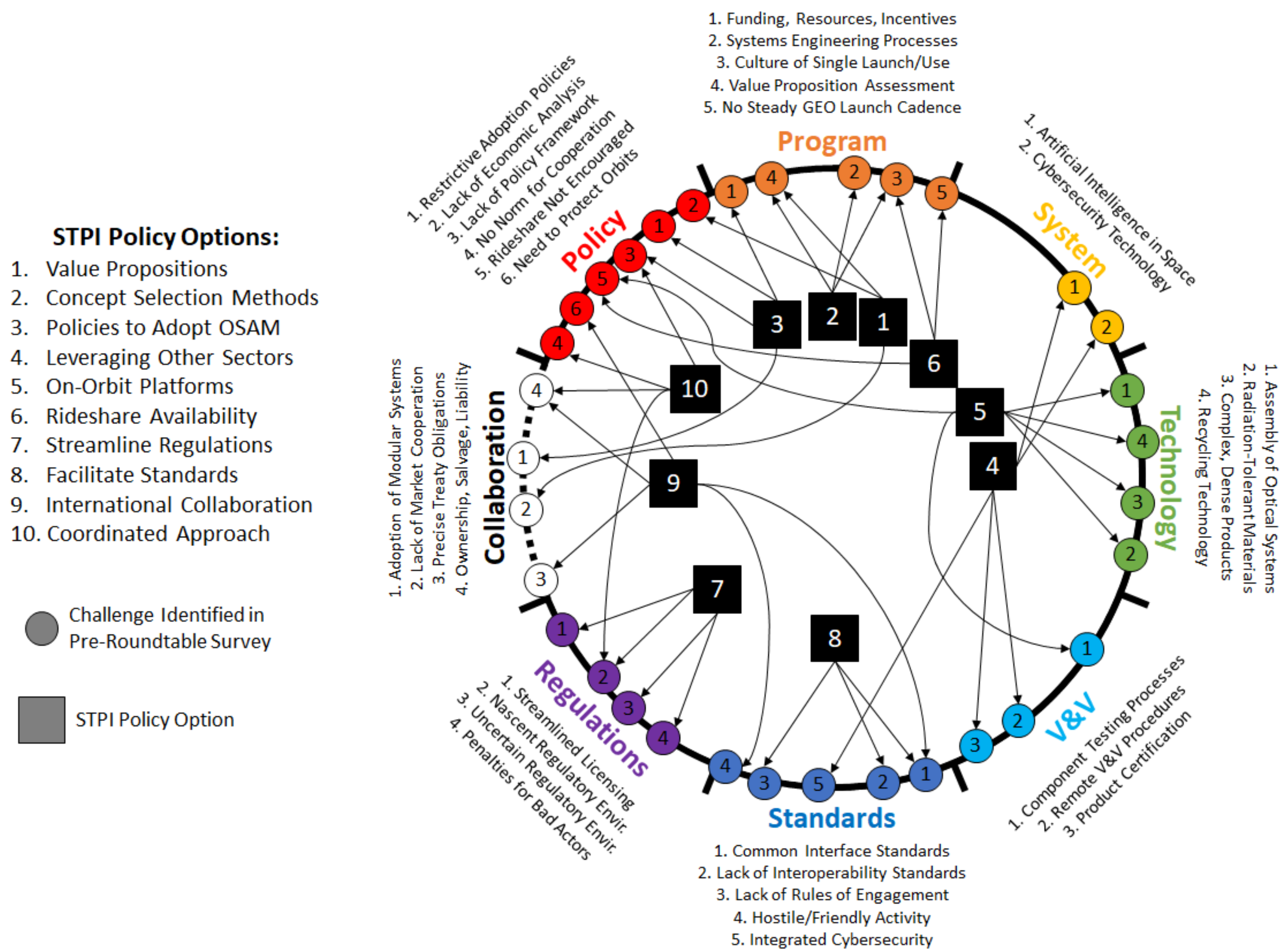

Figure 8: Mapping of STPI policy options to open wheel model and challenges identified in questionnaire

Appendix A.
List of Participants

Organization	Attendee
Aerospace Corporation	Gina Galasso
Air Force Research Laboratory	Richard “Scott” Erwin
Aura Astronomy	Matt Mountain
Chandah	Adil Jafry
DARPA	Fred Kennedy
DARPA	Joe Parrish
George Washington University	Henry Hertzfeld
Lockheed Martin	Jonathan Chow
Moog	David Chaves
NASA	Alvin Drew
NASA	Erica Rodgers
NASA GSFC	Hsiao Smith
NASA JPL	Jason Hyon
NASA LaRC	Keith Belvin
NASA MSFC	Raymond Clinton
NASA STMD	Trudy Kortes
Naval Research Laboratory	Michael Mook
Northrop Grumman	Jonathan Arenberg
National Reconnaissance Office	Byron Knight
Orbital ATK	Jim Armor
OSTP/National Space Council	Ben Reed
Secure World Foundation	Brian Weeden
Space Systems Loral	Mike Gold
Space Systems Loral	Al Tadros
Tethers Unlimited	Robert Hoyt
University of Illinois	Koki Ho
USAF	Joseph Gambrell
USAF	Keegan George
USAF	Douglass McCobb
Virgin Galactic	Richard DalBello

Appendix B.
Agenda

SCIENCE AND TECHNOLOGY POLICY INSTITUTE

Eisenhower Executive Office Building

1650 Pennsylvania Avenue NW, Washington, D.C. 20502

8:00 – 8:15 AM .... **Check-in**
Sara Carioscia, STPI

8:15 – 8:50 AM .... **Opening Remarks and Introductions**
Mark Lewis, STPI and Benjamin Reed, NSpC

8:50 – 9:00 AM .... **Goals and Plan for the Day**
Bhavya Lal, STPI

9:00 – 10:30 AM .... **Discussion: On-Orbit Servicing**
Moderator: Bhavya Lal

10:30 – 10:45 AM .... **Break**

10:45 – 11:45 AM .... **Discussion: On-Orbit Assembly**
Moderator: Iain Boyd, STPI

11:45 – 1:00 PM .... **Lunch**

1:00 – 2:00 PM .... **Discussion: On-Orbit Manufacturing**
Moderator: Ben Corbin, STPI

2:00 – 3:00 PM .... **Discussion: Roles of Government and Industry**
Moderator: Iain Boyd

3:00 – 3:15 PM .... **Break (Room Change)**

3:15 – 4:15 PM .... **Discussion: Roles of Government and Industry**
Moderator: Bhavya Lal

4:15 – 5:00 PM **Closing Remarks**

Mark Lewis and Benjamin Reed

Appendix C. Pre-Roundtable Questionnaire

Questionnaire

Current Activities

1. What organization(s) do you represent?
2. Please select all areas in which you are currently working or have expertise.
    a. Servicing
    b. Assembly
    c. Manufacturing
    d. Policy/Regulatory
    e. Other
3. If you are part of the private sector, what was your organization's average Internal R&D (IRAD) expenditure in 2017 for on-orbit servicing, assembly, and manufacturing? All responses will be kept confidential.

Goals of on-orbit servicing, assembly, and manufacturing (OSAM):

4. What types of space activities or stakeholders will benefit the most from OSAM?

OSAM Challenges and Solutions:

5. What are the **key challenges in technology development** that relate specifically to on-orbit servicing, assembly, and manufacturing of spacecraft? Please specify which area(s) you are referring to for each.
6. What are the **drivers and considerations** that contribute to each of these challenges?
7. What are **specific pathways forward** that could address these technology challenges?
8. What are the **key challenges in policy, law, or regulations** that relate specifically to on-orbit servicing, assembly, and manufacturing of spacecraft? Please specify which area(s) you are referring to for each.
9. What are the **drivers and considerations** that contribute to each of these challenges?
10. What are **specific pathways forward** that could address these policy, legal, or regulatory challenges?

11. What **lessons** can be drawn from **past space activities** to help solve current challenges to OSAM activities? What lessons can be drawn from **activities outside of the space sector**?

Government Roles in OSAM:

12. What steps, if any, should the Federal Government take for the United States to establish the lead in this emerging field–for technology development, policy and regulations, and setting norms of behavior?
13. Would a formal **interagency roadmap or strategy** for OSAM be useful?
14. If your answer to the previous question is yes, what are the **key milestones**? If no, what else could be done to facilitate the necessary progress?

Industry Roles in OSAM:

15. What steps should **industry** (both as users and providers) take to further OSAM activities?

Workshop Information:

16. What, if anything, would you like to **share at this workshop** with other Federal agencies and companies about your work in OSAM?
17. What **specific products or outcomes** would you like to see emerge from this workshop?
18. Are there any additional topics you believe are relevant that have not been covered in the questions above, or anything else you would like to share here?

Appendix D.
Questionnaire Responses

Summarized Responses to Questionnaire

Below is an analysis of the questionnaire responses STPI received prior to the roundtable. Repetitive or similar responses within each question were consolidated as appropriate, though there was surprisingly little overlap among responses for many of the questions. STPI organized responses for each question into appropriate topic areas. Most responses included more than one point per person, and not all respondents answered every question. Given that the survey was intended to be anonymous, responses are reported without attribution.

1. What organization(s) do you represent?

STPI classified the organizations that survey respondents listed as government, industry, non-profit, or academia. As Figure 9 shows, respondents almost equally represented government (6 NASA, 8 DOD) and industry (13 responses from 9 different companies). Note that 31 individuals submitted survey responses, although only 29 individuals attended the roundtable. Not all 31 of these responses were complete; not all questions were mandatory, so some respondents chose to answer only certain questions.

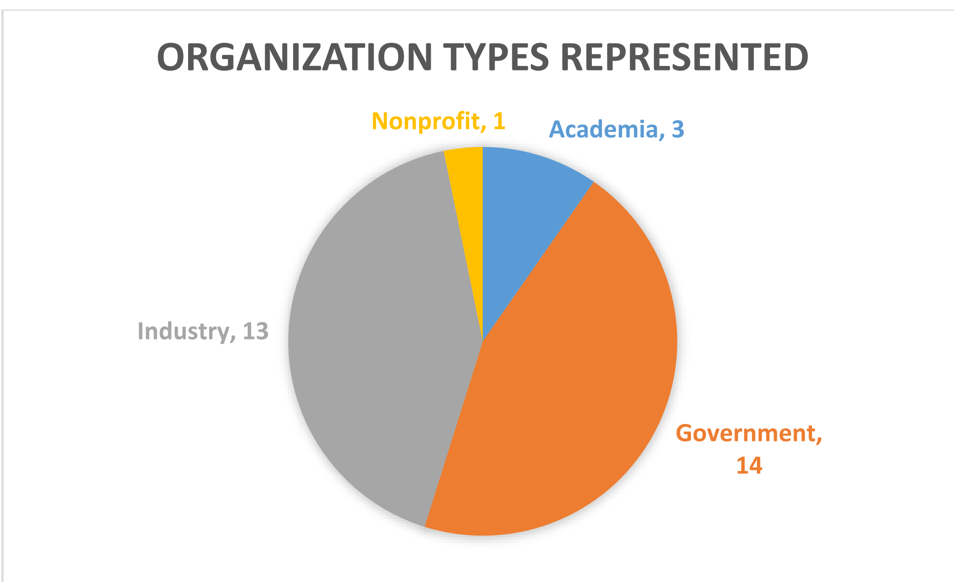

Figure 9. Organization Types Represented

2. Please select all areas in which you are currently working or have expertise.

Respondents were asked to identify their areas of expertise to provide some background for the analysis of their answers. STPI allowed respondents to choose from the following five areas: Servicing, Assembly, Manufacturing, Policy/Regulatory, and Other. Because respondents were able to select multiple options, a total of 89 areas were selected, as shown in Figure 10. Respondents selecting "Other" were asked to provide additional details. The 13 "Other" responses included variations on the following: interagency collaborations, on-orbit inspection, international standards, missions or systems architecture, systems engineering, technology, cyber security, optimization, and aerospace engineering.

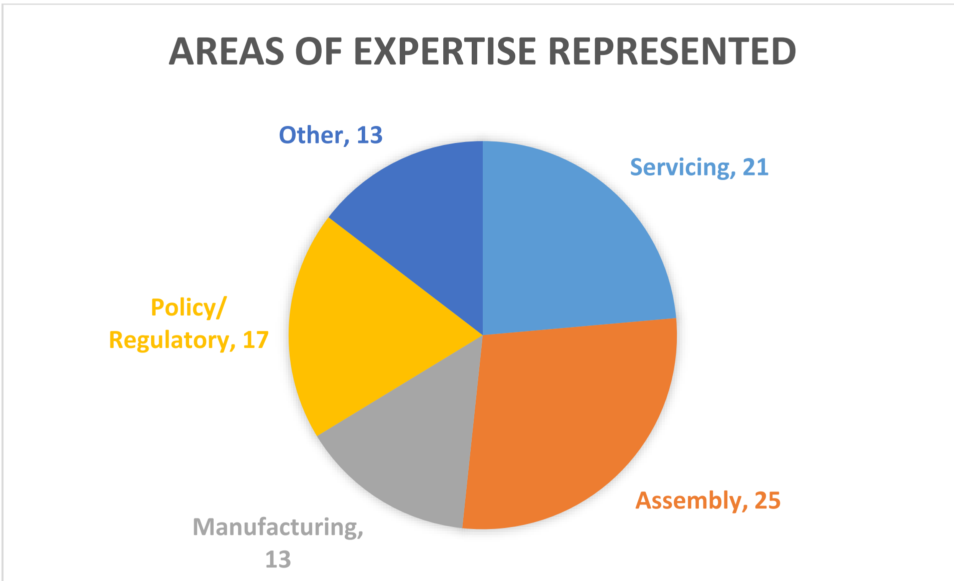

Figure 10: Areas of Expertise Represented

3. If you are part of the private sector, what was your organization's average Internal R&D (IRAD) expenditure in 2017 for on-orbit servicing, assembly, and manufacturing? All responses will be kept confidential.

Nine organizations responded to this question. Annual IRAD varied between $100,000 and $20 million per company, with a median of $5 million. Note that some of the respondents were large primes, and others were small startups. Total reported industry IRAD was $55–$60 million.

4. What types of space activities or stakeholders will benefit the most from OSAM?

- Within government, Air Force Space Command, the Intelligence Community (IC), NASA science and human exploration directorates, and entities that fly

Earth Observation and remote sensing satellites (e.g., DOC/NOAA/USGS) are expected to benefit from OSAM activities.

- Within industry, the likely beneficiaries are fleet owners and operators, satellite service providers, satellite manufacturers, and insurance companies.
- Activities fell into two main categories:
  - ***Enable modular structures and platforms larger than those currently feasible***. Supporting activities include: the deployment of larger apertures and power systems for telescopes, Earth observation systems, small satellites, etc.; the modular addition of more power and greater communications capability; the assembly of larger (including kilometer scale) and more capable spacecraft; and the maximization of payload capability.
  - ***Improve legacy fleet management***. Enabling activities include: increased operator awareness of asset health/inspection; repairing and refueling satellites; repurposing satellites; enabling extension of life and mission; expansion of capabilities (e.g., switching sensors to change or upgrade capabilities); and other logistical support.
- Application areas include:
  - Astrophysics missions
  - Commercial facilities
  - Crewed and robotic exploration missions and moon/planetary surface missions
  - Defensive and offensive space control
  - Missile warning
  - PNT
  - Remote sensing
  - Satellite communications
  - Signals and communications intelligence
  - Small satellites
  - Space-based ISR
  - SSA
  - Space tourism
  - Waypoints for exploration
- Advantages offered as a result of OSAM activities include a lower cost of mission (e.g., less time for verification, validation, and certification; reduction of launch cost), increased performance, decreased technology refresh time, longer life, increased resilience, and improved space asset management. OSAM activities and technologies are expected to make spaceflight more sustainable, affordable, and resilient.

5. What are the key <u>challenges in technology development</u> that relate specifically to on-orbit servicing, assembly, and manufacturing of spacecraft? Please specify which area(s) you are referring to for each.

Respondents noted similar challenges for technology development in all three areas (servicing, assembly, and manufacturing); however, these challenges have vastly different solutions depending on which activity is being considered (e.g., all areas need standards, but the types and applications of these standards are different across each activity).

Challenges in Technology Development Across OSAM Activities

- Program Level Challenges
  - Funding, resources, and incentive mechanisms are lacking for most of the necessary projects and technology advancements, and opportunities for funding are not always well communicated.
  - Traditional systems engineering lifecycle processes are either inadequate or unnecessarily burdensome (e.g., they can make OSAM less attractive to mission managers than traditional satellite options), especially for traditional integration and testing processes, but also for mission concept selection, mission operations, closeout, and verification and validation procedures.
  - Industry is accustomed to single-launch, single-use space systems. The culture of risk must be changed through increasingly capable flight demonstrations.
  - The business cases for OSAM activities need to be rigorously assessed to demonstrate that pursuing these capabilities will be worthwhile. These assessments should include: analysis showing ground-up differences in integration and testing procedures; mission identification and opportunities for demonstrations to determine which technologies can break into current ecosystems; and new missions or products that are enabled by OSAM, not just existing missions that are made more efficient or cheaper.
  - At this time, there is no steady cadence of launch to GEO for small inspection satellites.
- System Level Challenges
  - Specific challenges in robotics and AI include mission planning, trajectory design, control dynamics, integration of AI and sensors systems (especially in unusual and changing lighting conditions), mobility and manipulation, rendezvous and proximity operation (RPO) technologies, PNT, and grappling.
  - Cybersecurity is a concern, given that spacecraft that are able to interact with other spacecraft are a potential threat to national security interests. Preventing hostile actors from conducting aggressive or dangerous behaviors in space is essential to the preservation of the space environment.

- Processes for testing components and systems are lacking. A platform and pipeline to conduct experiments and demonstrations to advance the state of the art and reduce risk is required for these technologies to move forward.

- Standards and Practices
  - Common interfaces and standardized aspects and procedures throughout the enterprise (e.g., power, data, thermal, fluid) would allow for ease of ongoing services and updates to these systems. There is need for RPO procedures and rules of the road for interacting systems.
  - Remote validation and verification procedures will be necessary to approve technologies or activities that do not exist until they are in orbit.
  - Adoption and use of modular systems will be a key enabler for technology refresh, orbital replacement units, upgrades, assembly, and ease of autonomous operations, especially for servicing missions. There are also significant benefits for manufacturability, integration, and testing on the ground as well.

Challenges in Technology Development Specific to Servicing

- The system lacks cooperation: the existing market was not made to be serviced. There is not widespread agreement or clarity regarding what it means or entails for an asset to be "serviceable."

Challenges in Technology Development Specific to Assembly

- The assembly of optical surfaces and elements to a high precision and the optimization of assembly procedures are expected to be difficult.

Challenges in Technology Development Specific to Manufacturing

- There is a need for the materials and processes to manufacture radiation-tolerant, low-cost composite structures, as well as RF-quality surfaces.
- Complex, dense products such as circuit boards and optical instruments will be difficult to manufacture.
- Technology to recycle different materials on-orbit need to be developed.

6. What are the drivers and considerations that contribute to each of these challenges?

Drivers of Challenges in Technology Development Across OSAM Activities

- Program Level Challenges
  - Financial opportunities and sources of funding are not communicated widely and openly, and there are not enough opportunities and dollars to

support all interested actors. It will be crucial to institutionalize effective funding and incentive mechanisms to advance each technology, depending on its technology readiness level (TRL). The lack of funding will complicate the establishment of standards and prevent the resolution of technical issues that could otherwise be reasonably addressed.

  - The current system is plagued by a poor understanding of where costs and risk are incurred in the systems engineering lifecycle and where measures to increase cost effectiveness can be implemented.
  - The last 60 years in space have been dominated by a process of single launch with non-repairable assets (with the exceptions of ISS and Hubble), resulting in significant inertia against any efforts to change the process. The perception is that OSAM activities (particularly on-orbit integration, assembly, and testing) add significant risk to a mission.
  - There is not sufficient understanding outside of the science community about the immense benefits presented by an open platform on which to test technologies and conduct science. There is also not enough effort directed at understanding what products are economically feasible to fabricate or assemble in space, or what items or systems are uniquely valuable when produced in space—and communicating these values to potential customers.
  - Because small satellite up-mass to GEO has not been a commercial need, the launch service and cadence to support small satellites that could conduct inspection or minor servicing missions do not yet exist; such services could help build a market for inspection and servicing in GEO.

- System Level Challenges
  - Intelligence sufficient to make decisions without human input as well as multi-agent autonomy with distributed situation assessment and coordinate control are not adequately developed. The on-board computational and data storage capabilities required for verification and validation of complex models are needed.
  - Cybersecurity is restricted when tools, technologies, policies, and training to protect all OSAM computing systems against unauthorized use, disclosure, disruption, modification, or destruction to ensure confidentiality, integrity, and availability are not integrated throughout the design and development of an asset.
  - Insufficient experience with in-space robotic tools and techniques restricts processes that can conduct effective tests; this can be addressed by a multitude of flight experiments, prototypes, and entrepreneurial activities.

Flight experience is necessary for all OSAM technologies. Currently, facilities to test rendezvous and proximity operations do not exist.

- Standards and Practices
  - The current system does not support discussion about each involved entity's expertise and available technologies; forums for discussion or mechanisms to spread this information are needed.
  - Prime contractors have a vested interest in keeping their interfaces and approaches proprietary. They have invested time and funding into developing those interfaces that give them a competitive advantage over other contractors. Making that intellectual property public by standardizing it across the industry gives their competitors that technology—without their competitors using their own IRAD to develop competing alternatives. Other incentives need to be in place to encourage standardization to offset the perceived loss of a competitive advantage as a result of standardization.
  - The difficulties in validating and verifying OSAM activities and the resulting systems are driven by the difficulty of confirming a number of quantitative performance metrics including: qualifying mission-critical components that do not exist until they are manufactured on orbit; developing and qualifying sensors to detect and assess failures or unacceptable quality; and modeling simulations for sequencing, planning, assembly, and manufacturing.
  - The institutional momentum behind every satellite company's design paradigm prevents the switch to modularity and serviceability.

Drivers of Challenges to Servicing Technology Development

- Because the commercial market is not driving OSAM, it is not pressuring cooperation (e.g., create standards, decrease prices, design satellites to interact). Norms or standards that would enable or, eventually, require newly-designed satellites to be serviceable are not yet being widely discussed.

Drivers of Challenges to Assembly Technology Development

- Some challenges will be solved through increased practice and demonstration opportunities; the current lack of these large structures minimizes the opportunity for entities to test and develop these technologies.

Drivers of Challenges to Manufacturing Technology Development

- The development of the necessary technologies is likely to be limited by the cost and availability of power on orbit.

7. What are specific pathways forward that could address these technology challenges?

Pathways in Technology Development Across OSAM Activities

- Program Level Challenges
  - Coordinated funding could address requirements for technology development, as defined by a consortium of commercial and government parties. The government could serve as a customer for new architectures and use further funding to reduce risk in strategic technologies. The government can thus create economic incentives for the larger community to participate synergistically and leverage work already being done in other applications, especially on the ground.
  - A rigorous study of what drives cost and limits space systems design, development, lifetime, and utility would benefit and streamline the engineering system.
  - A clear assessment of the costs and benefits of OSAM would outline the opportunities in each potential endeavor. Understanding the value proposition of persistent platforms with short-lived payloads could help push the research and development phase of these technologies. This could be further supported if OSAM activities are designed and developed in comparison with state-of-the-art designs. Additionally, this could be enabled by public private partnerships and more clear terms and definitions for these collaborative relationships.
  - More efficient technology transfer could help with widespread adoption and use of new technologies. The government's "too big to fail" mentality needs to shift to a more agile paradigm that permits and encourages the repair and upgrade of assets.
  - Rapid cadence of and ride-share opportunities for secondary-class payloads, especially to GEO, could be used to validate and evolve OSAM technologies.
- System Level Challenges
  - Robotic and artificial intelligence endeavors could be supported by the development of technologies that strengthen system health management, multi-agent coordination, and automated decision-making.
  - Protective measures for cybersecurity should be applied throughout the process—during pre-formulation, design, and operation.

    - To improve the availability and efficacy of testing, low-cost technology experiments and demonstrations could be enabled by lower launch costs and modular systems like the Defense Advanced Research Projects Agency's (DARPA) PODS. Efforts can be made to establish ground-to-space incubator or experimentation programs aimed at increasing knowledge in specific technology areas. Practice and experience are necessary, and conducting these activities on the ground initially can help reduce the risk.
- Standards and Practices
    - Effective integration of government, industry, and academia is needed. Government should clearly articulate goals; academia should develop fundamental technology at low TRLs; and industry should develop applied high-TRL technology and spacecraft. Working groups could be established to define the integration and testing qualification requirements for OSAM (e.g., by expanding the scope of CONFERS). Collaborative technology development among prime contractors could support these efforts. Open communications, implemented through forums dedicated to developing and sharing technologies, can support these collaborations. A coordinated effort will be required to ensure stakeholders are not competing unnecessarily and to protect against technology gaps; such coordination can ensure mutual benefit without stifling competition. More efficient technology transfer from NASA and other government programs would allow for further collaboration. The OSAM enterprise would benefit from the development of an overarching strategy.
    - The U.S. should develop national interface design standards. This effort could then expand to include other nations in a broad coalition to define international standards.
    - A new regime for validation and verification of systems, supported by increased testing opportunities, will allow these technologies to proceed. Flight demonstrations could help lower the risk of OSAM capabilities.
    - New space systems should be designed to be modular with plug-and-play interfaces. Educated customers could push their contractors towards modularity to better enable future upgrades and maintain and meet contracted goals.

Pathways in Technology Development Specific to Servicing

- Servicing could be supported if entities develop and encourage more cooperative satellites and space systems throughout the industry that can leverage OSAM opportunities to improve the value of missions over their potential lifecycles.

Pathways in Technology Development Specific to Assembly

- Ground-based demonstrations of assembly in relevant environments could help the development of necessary technologies.
  - Repeatable module-to-module interfaces for in-space assembly of multiple geometries could help the development of high-precision technologies and systems.

Pathways in Technology Development Specific to Manufacturing

- Technology could be furthered by ground-based demonstrations of additive manufacturing in relevant environments.

8. What are the key challenges in policy, law, or regulations that relate specifically to on-orbit servicing, assembly, and manufacturing of spacecraft? Please specify which area(s) you are referring to for each.

Challenges in Policy

- Some policies may be restrictive to emerging technologies, limiting OSAM activities.
- A systems engineering and economic analysis for the potential OSAM technology investment portfolio is lacking.
- The lack of a current policy framework might prevent the emergence of a marketplace for OSAM.
- Current policies do not make cooperative servicing the norm and therefore an industry expectation.
- The current framework does not necessarily encourage rideshare launches, which could be beneficial for testing new technologies.
- Current policies do not ensure the U.S. will maintain supremacy in the area. If the U.S. does not remain ahead, another entity may set norms of behavior, challenging U.S. activities.
- Current efforts in SSA/STM are insufficient for ensuring safe operations. For example, policies could be implemented to protect valuable orbits (i.e., assets could be mandated to conduct servicing activities only in a graveyard orbit to minimize disaster in the event of an accident).

Challenges in Standards

- The lack of interoperability for commercial and government systems as well as general interface standards could limit collaboration. The absence of consistent

CONOPS standards for both private and government operations further restricts this cooperation.

- Processes for product certification are not in place, making design and development difficult.
- The absence of standards that outline rules of engagement as well as rendezvous and proximity operations prevents the assertion of a more clear system of behavior, which would allow entities to prepare for future activities and events.
- A system needs to be in place to differentiate between commercial/normal activity and potentially hostile activity, which would help protect assets while avoiding unnecessary altercations.
- Cybersecurity needs to be integrated and enforced in these systems, especially considering the interactive nature of OSAM activities.

Challenges in Regulations

- The licensing process for space activities in general need to be streamlined.
- The regulatory system for OSAM activities is nascent; there are few hurdles, especially for inspection. Existing rules should not be blindly enforced.
- The uncertainty in regulations allows for creativity. However, the regulations do not address specific questions about actions necessary for OSAM activities (e.g., can end-of-mission disposal requirements be waived for persistent platforms? Is recycling a proper way activity to satisfy end-of-mission protocols? What entities can authorize permission for rendezvous and docking operations?). The regulations also do not address potential future applications, such as processes for connecting to space internet.
- Failure to enact penalties for disrupting OSAM or other space systems could present opportunities for bad actors.

Challenges in the Outer Space Treaty and International Obligations

- Treaty obligations need to be defined more precisely. In addition to general rules of engagement, increased treaty analysis could set norms for procedures in the event of an accident or close approach between spacecraft from different national entities. Some respondents suggested updating the Outer Space Treaty to specifically consider both national and commercial OSAM activities.
- Other areas that may require international discussion and negotiation include liability, RF interference, salvage rights, and ownership.

9. What are the drivers and considerations that contribute to each of these challenges?

Drivers in Policy Challenges

- The development of government and military offensive counterspace capabilities, specifically co-orbital ASATs, coupled with growing concerns about future conflicts extending into space, may help push policies intending to preserve space activities.
- The lack of effective SSA contributes to these concerns and may serve as an additional motivation to pursue protective policies. More entities are becoming concerned that in the continued absence of these and related policies, important orbits may become unusable, as stakeholders will be left without the ability to remove debris.
- There is lack of coordination in the U.S.—both within the government and between government, industry, and other stakeholders. A more collaborative community would enable easier determination of which entity is taking the lead on what aspect of OSAM activities and the supporting technologies.
- In some cases, the political will to actually make decisions and implement new regulations seems to be lacking in the U.S. Bureaucratic inertia is preventing forward progress in developing policies to support these systems (e.g., because cooperative servicing is currently not the norm, it will require a new mindset or paradigm before it can be implemented).
- Other policy failures are the result of a lack of funding, focus, time, and expertise.

Drivers in Standards Challenges

- In some cases, there is not sufficient knowledge about the processes for establishing standards (e.g., product certification). Once agreed upon, standards need to be implemented quickly.
- An enforceable system needs to be implemented to ensure that servicing is only used to access assets that are approved by the owner/operators.
- Developing technologies and standards that are easily adaptable to various spacecraft and launch vehicles is key to the broader adoption of these activities.
- Failure to integrate cybersecurity into OSAM missions in the early planning stages will complicate future cybersecurity standards. The absence of processes to collect and maintain system health information and decision tools further complicates cybersecurity efforts.

Drivers in Regulatory Challenges

- A clear regulatory environment for new and emerging activities does not exist; as new technologies are developed, regulations need to be established.
- There is currently significant uncertainty regarding mission authorization and supervision related to OSAM activities.
- Existing controls regarding remote sensing are counterproductive. The current lack of IP protection, particularly with images, may constrain collaboration or production in the future.

Drivers in Treaty and International Obligation Challenges

- The absence of well-defined international salvage and property protocols, compounded by the fact that the Treaty was not written with the commercial sector in mind, makes establishing policies and rules based on these obligations challenging.

10. What are specific pathways forward that could address these policy, legal, or regulatory challenges?

Pathways in Policy

- Support from NASA, DARPA, and other government agencies for policies enabling OSAM and other space activities is critical.
- Identifying upcoming technologies and missions that will be relevant for potential new industries and space activities, as well as the corresponding policies and regulations, will help OSAM move forward.
- Investment in studies on economic analyses and commercialization pathways for OSAM technologies could help entities identify which capabilities would be particularly valuable to pursue through OSAM (e.g., what cannot be done through a single launch) while clearly communicating cost, risk, benefits, and technical information to stakeholders. Potential policies could be supported by rigorous economic analyses of commercialization paths of OSAM technologies that consider expectations of stakeholders and their interactions.
- Entities could fund programs to quickly design, build, and test hardware for OSAM activities. Infrastructure could help commercial entities get to and operate in space to gain experience.
- Improved SSA and data sharing between countries could help with collaborative policies moving forward.

Pathways in Standards

- Standards, modularity, and other OSAM-related technologies could be required aspects of future acquisitions for large projects, both government and commercial.
- Industry and government forums (e.g., CONFERS) and voluntary standards bodies can help address challenges, create interface and other standards, identify preferred incentive mechanisms, increase coordination and cooperation, and address technical and regulatory issues. The government could help by identifying relevant parties that should be included in these conversations, establishing deadlines for their formation and other deliverables, ensuring the standards are adopted, and minimizing perceived contractor favoritism.
- A system could ensure that the entities developing groundbreaking cooperative servicing technologies know the procedures for making them an industry standard (e.g., cooperative service valve, fiducials, grappling fixture).
- In addition to industry standards, countries could pursue agreements between militaries that clarify norms of behavior for military space activities.

Pathways in Regulations

- An assessment of current and potential regulatory environments, both domestically and internationally, would be useful for providing a stable, effective regulatory regime. For example, one respondent recommended removing the requirement of a commercial remote sensing license for nearby (less than 5 km between satellites) satellite inspection and RPO.
- In the short term, existing policy, legal, regulatory rules should be interpreted to allow as many commercial OSAM operations as possible in order to set positive precedents and help entities gain experience.
- The regulatory system needs to take a proactive, rather than a reactive, approach (e.g., working with industry to develop regulations before a major accident or international incident occurs, rather than after, without placing a significant regulatory burden on industry up front).
- Servicing activities require greater regulation to mitigate the possibility of operations failure that may create debris problems, as well as to promote other best practices.

Pathways in Treaty and International Obligations

- The U.S. should work with international partners to get worldwide buy-in for standards and verification approaches for OSAM activities.

- The U.S. interagency (likely via the National Space Council) could prescribe international rules of the road or norms of behavior as part of a system that promotes free enterprise and sustainable space.
- Specific procedures for handling potential trans-national issues need to be developed. The system should anticipate unexpected events and have a process in place to handle them.
- One respondent recommended updating the Outer Space Treaty to specifically address new applications such as salvage and OSAM activities.
- One respondent suggested implementing an international space policy that permits orbital debris removal by any country.

11. What lessons can be drawn from past space activities to help solve current challenges to OSAM activities? What lessons can be drawn from activities outside of the space sector?

Specific Lessons Learned

- Current challenges could likely be solved with a broad approach, which develops all aspects of OSAM, rather than a piecemeal approach.
- Space should be treated like any other commercial business area, where business cases determine the direction, standards, and technologies. The U.S. Government should establish a positive framework for business (e.g., rules of the road, norms of behavior), safety, and environmental preservation (e.g., debris, sustainable space).
- The importance of a robust investment portfolio, as well as the potential for cost and schedule overruns in technology development, should not be underestimated. Potential problems, both domestic and international, should not be ignored.
- Enough money should be devoted to on-orbit programs and projects to make real-time adjustments in response to evolving or unexpected situations.
- Because the space industry has strong government and international equities, entrepreneurs need to pay attention to the regulatory landscape to best manage stakeholder expectations.
- OSAM activities and applications need to be open to the public market, not just for the uses and applications of the DOD.
- Past OSAM activities and experiments have contributed to technology progress as well as operational knowledge; these investments and developments should be built on.

- Many technologies outside of space have general applicability to the space economy. Incentivizing the actors behind those efforts to address and include potential space-related applications can allow space entities to draw on and benefit from that experience.
- Many new technologies and missions have been supported and ultimately accomplished due at least in part to the requirement to permit rideshare on launches; rideshare can enable testing, technology maturation, and implementation of OSAM technologies as well.
- There should be clear lines of responsibility at all levels, and projects should include people with various backgrounds: people who understand space and space operations, as well as people who understand robotics, manufacturing, additive manufacturing, integration and testing, logistics, economics, policy and politics.
- Large contractors should establish relationships with suppliers in order to keep track of where parts are being built to avoid supply chain disruptions and find alternative suppliers if some go out of business.

Parallels to OSAM Challenges in the Space Sector

- While providing experience using servicing technologies, Hubble also demonstrated the benefits of modularity and cooperative servicing design for in-space operations, ground integration, and testing.
- In addition to demonstrating manufacturing in microgravity, the ISS facilitated the development of standards, which allowed a variety of vehicles to contribute and enabled a wide suite of servicing paradigms.
- Many space programs have demonstrated the importance of establishing a broad base of technical buildup to prevent technical gaps or bottlenecks.

Parallels to OSAM Challenges in Non-Space Sectors

- Past challenges in systems engineering have demonstrated the importance of collaboration between personnel with a spectrum of technical expertise.
- The Outer Space Treaty and Paris Climate Agreement are two major treaties involving many countries that have agreed to a set of goals and objectives for the benefit of humanity. A parallel could be used for OSAM standards, practices, agreements, and norms.
- In the maritime domain, norms, standards, and agreements were established to discriminate between peaceful and hostile activities and address additional commerce rules. Similar processes were followed in Antarctica and through International Civil Air Traffic processes.

- Substantial investments were made in the aviation industry to establish standards for qualifying additive manufacturing processes of mission-critical parts.
- Entities pursuing OSAM activities can leverage investments in AI, self-driving cars, and other robotics systems as well as lower-level systems like sensors, processing, algorithms, and machine learning.
- The energy sector successfully leveraged private capital for large initiatives.
- Development of the Internet has led to focus on other issues including the Internet-of-Things, cybersecurity, and industrial control issues. These issues will all be relevant to OSAM operations in the future.

12. What steps, if any, should the Federal Government take for the United States to establish the lead in this emerging field, for technology development, policy and regulations, and setting norms of behavior?

Funding

- The government could establish and adopt a framework to encourage and institute fast, iterative flight programs that will allow for incremental technology development, experiments, and demonstrations.
- The government should make substantial investments in technology development, including tipping point technologies, as well as flight demonstration and maturation programs.
- Intelligent use of long-term U.S. institutional capital for funding ventures should be encouraged. The government should provide technical leadership and guidance, especially high-level leadership early on to attract investors.
- The government should engage in public-private partnerships in which it supports initial infrastructure development and overall risk reduction.
- The government could create funding and incentive mechanisms for a large community, to include industry, small businesses, and academia.
- Consistent funding for NASA Space Technology Mission Directorate (STMD) initiatives and objectives would help push development and maturation of OSAM technologies.
- Multiple parallel efforts should be pursued to prevent a single entity from establishing a monopoly.

Technologies and Missions

- A goal should be for the U.S. to be the first to demonstrate OSAM technologies, which will help establish global leadership.

- Government could create new programs that will demand new technologies and capabilities (e.g., require servicing on all government-sponsored spacecraft). Within these programs, commercial space capabilities should be used as often and early as possible, and competing government programs should not be created. For example, a U.S. Government constellation could be established that is designed to enable frequent technology refresh by a servicer; these capabilities could be fulfilled through contracts.
- A timeline for U.S. Government missions that will use or rely on OSAM technologies would help the government lead the development of requirements for these activities. Deciding what OSAM capabilities the U.S. intends to employ—and how these will be utilized—will help drive standards, such as interfaces. For example, the government could identify servicing provisions that a client spacecraft could incorporate to facilitate servicing. A robust, long-term portfolio designed to integrate efforts from multiple sectors could support these plans.
- Government development programs should focus on raising the TRL for systems and operations that are considered critical for future OSAM-based operational missions. Government should also support ground-based risk reduction efforts for development and demonstration of critical technologies.
- Infrastructure created by the government (e.g., depots, testing platforms) could allow the private sector to develop commercial services without bearing the initial upfront cost. A servicing platform would allow entities to design satellites to be refueled and repaired, setting the U.S. apart by having more resilient and sustainable space assets.
- NASA's technology transfer strategy should be leveraged, giving any interested U.S. company access to NASA's technologies that is has developed and proven.

Organizations

- Relevant government organizations should participate in panels that include both government and industry stakeholders to develop standards. The government could survey U.S. industry to understand an optimal environment that would accelerate technology development and satisfy industry needs.
- Existing S&T Partnerships for in-space assembly (NRO, NASA, Air Force) should be expanded and used as models for potential future collaborative opportunities (e.g., the government could establish a National Robotics Information Sharing and Analysis Center).

Standards

- The government should establish standards for numerous OSAM needs. The Federal Government has already taken steps in some of this by developing CONFERS. In the future, it could lead an effort to standardize future services for GEO satellites; facilitate establishment of standard interfaces for assembly of modular space systems; and support efforts to make cooperative servicing designs the norm and industry standard.
- The U.S. could demonstrate leadership and encourage international participation in the development of norms and standards to ensure international buy-in and cooperation.
- NASA's Satellite Servicing Projects Division has already established Cooperative Servicing Aids to facilitate servicing in the future. These guidelines could be used to create standards as the field matures.

Regulations

- The government should establish a transparent national regulatory and oversight environment, which clearly defines liability and outlines possible and permissible steps for the management of space debris. This can serve as a starting point for the U.S. to play a role in defining an internationally recognized regulatory environment.
- Policies should ensure a level playing field for private entities (e.g., avoid high barriers to entry). As part of this effort, the roles for all licensing organizations could be assessed and improved, as prompt licensing could support commercial OSAM activity. An efficient licensing system would also help encourage other countries to license in the U.S., as it would demonstrate a standard for space activities and operations.
- The government could retain the United States' competitive advantage by ensuring that sensitive technologies and information are not shared with unfriendly actors (e.g., proper export control systems, especially for ITAR-controlled technologies).
- The government could clarify regulations for orbital data requests, such as SSA data requests, for OSAM missions.

13. Would a formal interagency roadmap or strategy for OSAM be useful?

Respondents were able to explain why or under what circumstances an interagency roadmap or strategy for OSAM would be useful. 19 survey respondents gave answers with varying levels of specificity. To best represent these details, STPI classified their answers on a spectrum, as shown in Figure 11.

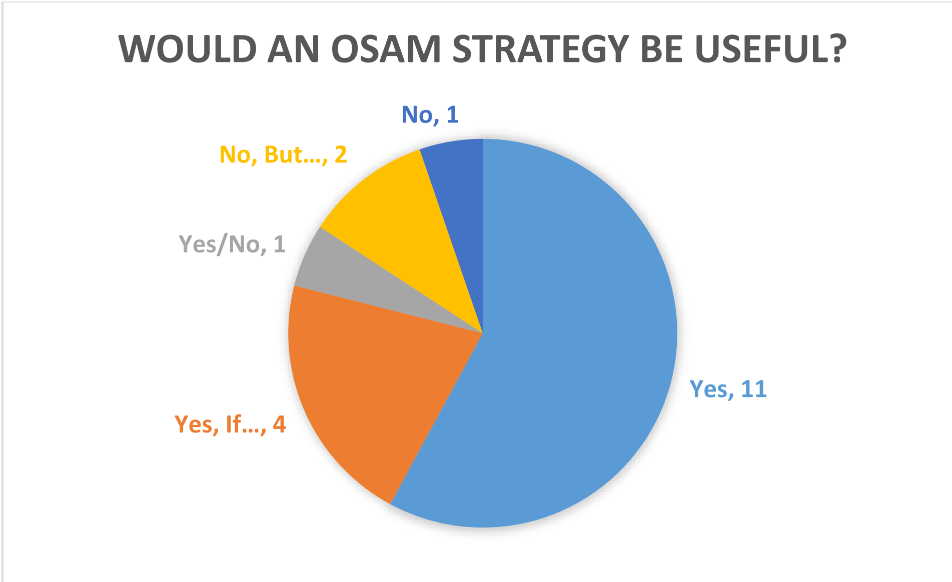

Figure 11: Responses to OSAM Strategy Question

Reponses Classified as "Yes"

- Yes, such a document would be very useful for planning.
- Yes, with investment behind it.
- Yes. It could involve NASA, DARPA, and other U.S. Government players on the client side, as well as commercial GEO communication satellite providers and operators.
- Yes. The roadmap needs to be robust and capable of capturing a consistent and effective technology investment portfolio across NASA, DARPA, DOD, and even NSF.
- Yes; this will help industry meet the government needs and direct their research
- Yes, an interagency roadmap (to include DARPA and NASA) for in-space assembly & OSAM would be very useful.
- Yes, it would be useful to integrate into a National Roadmap the NASA Technology Roadmap, NASA Strategic Technology Investment Plan, DARPA robotic research, AF technology research, and automotive research.
- Yes, I believe integrated activities are always helpful.
- Yes, it would be useful. Benefits could be realized by compiling envisioned requirements for these systems and structuring this into a roadmap.

Reponses Classified as “Yes, If…”

- Yes, but only if the strategy is kept at a very high level, since there are many competing technical approaches.
- Yes, if it is aligned with requirements and resources.
- One respondent noted that roadmaps are difficult since time is a function of investment. However, they also asserted that a strategy is definitely needed to guide which actors should be pursuing which technologies or efforts. This would help ensure U.S. leadership moving forward (e.g., the United States’ loss of leadership in hypersonics is not something that should be repeated with OSAM).
- One respondent suggested first generating a need database from industry before developing a roadmap; this database could promote buy-in from stakeholders.

Reponses Classified as “Yes/No”

- A roadmap or strategy would not be useful for technology, but could be effective for policy, regulation, and licensing.

Reponses Classified as “No, But…”

- Although a roadmap could define overlaps in OSAM projects and develop a process to deal with these common issues, a single document would likely not be useful, since each category (servicing, assembly, and manufacturing) may need a separate strategy to address specific issues and next steps.
- One respondent suggested that specific department or agency technology roadmaps might be more useful, given that an interagency roadmap could stifle or skew commercial investment and pursuits. However, an interagency strategy that is focused on removing policy/regulatory/licensing constraints from commercial OSAM might help. An enforced policy that says it would be useful if U.S. Government programs were required use commercial OSAM services before working to develop an independent U.S. government system could be useful.

Reponses Classified as “No”

- One respondent said the U.S. does not need an interagency roadmap or strategy. Once there is a better understanding across agencies of how OSAM capabilities will be used, these collaborative efforts (e.g., common interfaces) may be considered.

14. If your answer to the previous question is yes, what are the key milestones? If no, what else could be done to facilitate the necessary progress?

Funding

- The roadmap could detail or necessitate funding for several of the currently proposed OSAM missions (e.g., RSGS, Restore-L, NASA Tipping Point, DARPA PPG), as well as the next round of demonstration missions.
- Language in the roadmap could specify funding for the development of requirements in each agency.
- Specifically, the roadmap could fund "Space Challenges" to encourage small teams and commercial companies to advance technologies that are derivative of existing Earth-based technologies.

Information Gathering

- The roadmap could outline OSAM requirements for each agency (NASA, DOD, etc.) and review and share these with industry to support commercial development.
- The roadmap could articulate government needs, preferences, concerns, goals, objectives, and target dates. Industry could build business cases based on these requirements, expected opportunities, and need dates, supported by potential design and cost studies exploring the use of OSAM for NASA/DOD/NRO space missions. These efforts could provide a broad assessment of the market space and industry needs.
- Assessments (e.g., the Air Force Space Command assessment to be completed by April 2019) that document and prioritize capability gaps and identify required capabilities, operational characteristics, and attributes of OSAM systems could be supported by a roadmap.
- One respondent suggested writing the first draft of an OSAM roadmap before the end of this year, with annual updates to keep pace with the evolving market and technology.

Organizations

- The development of OSAM could be promoted through a national technology development and implementation project.
- A roadmap could expand the scope of CONFERS could be expanded to include OSAM, or establish a parallel to CONFERS to establish standards and determine regulatory issues for OSAM. Industry engagement could be a focus of the roadmap.

Technologies

- An interagency technical roadmap could prioritize the necessary technologies. For example, the OSAM Roadmap could be added to NASA's Technology Roadmaps, Air Force Space Enterprise Vision, etc.
- The roadmap could specify the technologies necessary to enable the on-orbit assembly and manufacturing of apertures in various size classes and frequency ranges.
- Once the necessary technologies are established (e.g., robotic systems, assembly elements, in-space manufacturing), entities can begin to develop milestones unique to those technologies (e.g., prototyping, environmental testing, lab demonstrations). Specific technology demonstrations include: developments for assembly capabilities needed to reduce risk; the assembly and maintenance of serviceable platforms addressing multiple mission needs; and the robotic manufacturing of components in space, from rudimentary to exquisite objects through multiple iterations.
- Potential mid-term milestones (2021-2025) include: enabling terrestrial and space-based technology demonstrations (e.g., using WFIRST); miniaturization of components to support SWAP goals; and experimentation with terrestrial collaborative heterogeneous teams or using the ISS.
- Potential Long-term Milestones (2026-2030) include the collaborative assembly of prototype structures by cognitive robot teams, as well experiments building structures in space using various new material technologies (e.g., meta-materials).
- Non-classified applications and technology should be as transparent as possible.

Missions

- One key for this technology roadmap would be identifying milestones where certain elements come together. The efforts toward each milestone may be interrelated; these interactions need to be captured beforehand. For example, a robotic arm intended to manipulate a structural element should be demonstrated to function alongside the element at certain milestones.
- Government and industry need to negotiate key milestones. According to one respondent, these milestones are expected to be organizational and economic, not technological.
- Milestone missions could follow a general path of 1) technology demonstration flight missions, 2) short-term missions with depots, and 3) long-term sustainable missions with permanent on-orbit platforms.

- Milestones depend on the specific requirements and the associated flow down to the technical approaches to achieve these requirements. For example, there are more than 20 technologies requiring maturation for one specific cryogenic fluid management technique alone, which is only one element of spacecraft servicing. Other techniques in OSAM have similarly complex hierarchies of technology development needs.

Standards and Regulations

- The roadmap can help entities identify and develop national interface design standards for OSAM. Part of this process could include the identification and implementation of national cybersecurity standards and processes.
- The roadmap could outline opportunities for industry and Congress to communicate and work toward pro-commercial regulations and licensing processes. This increased focus on commercial involvement could ensure that U.S. OSAM policies remain ahead of foreign regulations to incentivize businesses to stay in the U.S.
- One respondent suggested that the roadmap could outline a path toward updating the Outer Space Treaty to include OSAM and salvage rights.

15. What steps should industry (both as users and providers) take to further OSAM activities?

Funding and Business Models

- In order to build profitable business cases to attract investors, commercial entities could identify the information necessary to refine business models and work to understand customer needs, in order to identify areas of cost saving and challenges.
- Industry could assess and articulate the value of new products and services.
- Industry should continue making IRAD investments in OSAM while co-investing in technology advancements.

Missions and Technology

- Private entities could partner with government in underserved technical or programmatic areas, and industry could continue to develop and demonstrate OSAM capabilities in collaboration with DOD and civil partners. Efforts could begin by developing services and space systems that capitalize on the benefits provided by OSAM capabilities (e.g., deploy technologies and architectures that have commercial support for sustained business). Innovation on various architectures and techniques could continue from there.

- Spacecraft should be designed to facilitate on-orbit robotic repair and maintenance.
- Efforts should be taken to improve cybersecurity in the design, test, and continuous monitoring of space systems. Cybersecurity should be integrated into the system structure for all AI and autonomous operations.

Cooperation and Communication

- Prime contractors can provide mentorship or sponsorship for smaller emerging companies (e.g., those receiving SBIR funds) that pursue OSAM technologies or activities. Industry entities can form communities to share vulnerabilities and work to mitigate them.
- Private entities should collaborate when possible and work closely with the major customer (i.e., government) to develop procedures as needed.
- Entities should take proactive steps to be transparent about their OSAM activities and remain open and transparent with the U.S. Government regarding plans and anticipated support needs.
- Industry can support organizations in the U.S. that evaluate global trends and survey technical innovations, helping commercial entities capitalize on these opportunities.
- Marketing OSAM capabilities to end-customers could encourage both support for the technology development and ultimately purchasing of the services. Industry could educate government and private customers on OSAM benefits, best practices, and shifts in possible design and operations procedures. Additionally, private entities can stress the national importance of OSAM to congressional stakeholders, emphasizing both the economic and strategic benefits.

Standards and Regulations

- Industry should take a lead role in developing standards for OSAM activities, potentially by creating and participating in forums and standards organizations. As spacecraft bus manufacturers, some private entities can lead the development of spacecraft serviceability provisions.
- Industry should be involved in the development and adoption of regulations to help globalize OSAM regulations and standards that are supported in the U.S.

16. What, if anything, would you like to share at this workshop with other Federal agencies and organizations about your work in OSAM?

Respondents offered program details, goals, technologies, and next steps. These include:

- Progress in commercial on-orbit inspection activities
- DARPA's Robotic Servicing of Geosynchronous Satellites (RSGS) program
- NASA STMD's vision, strategy, and current efforts
- Technologies developed by NASA's Satellite Servicing Projects Division (SSPD)
- An overview of NASA's efforts in on-orbit robotic manufacturing and assembly
- The significance of academic research in OSAM planning, policy, and economics, as well as research in engineering and optimization
- The In-Space Assembled Telescope (iSAT) study
- Aerospace and Air Force Space and Missile Center's work to increase DOD's space resiliency

Topics for further discussion include:

- The technologies necessary for the U.S. to remain a global leader, in space generally and in OSAM specifically
- The need for a study of the economics of OSAM
- The establishment of standards and timelines for OSAM activities
- The need for IP and in-flight experiments
- The state-of-the-art for in-space assembly and manufacturing
- Prospects for near- and medium-term mission infusion
- Leveraging work in sectors outside of space

17. What specific products or outcomes would you like to see emerge from this workshop?

Five respondents identified the discussion or development of a roadmap as a desired outcome of the workshop. Summarized descriptions of the desired roadmap follow.

- A roadmap that clearly states both technical and policy/law options and responsibilities, particularly for common and over-arching issues.
- A roadmap that outlines engagement with industry (including CONFERS) and offers a path to updating the Outer Space Treaty to include servicing, assembly, and salvage rights.

- A roadmap for development of standards for OSAM activities.
- A push for an interagency roadmap that includes a plan to fill specific needs for OSAM, which will begin to inform an investment strategy.
- A discussion of the benefits of creating an interagency roadmap, a decision on whether to proceed with development of such a roadmap, and, if positive, an outline of next steps.

Many respondents hoped the workshop would set out future steps for increased communication and coordination regarding OSAM. These included:

- Common definitions of on-orbit servicing, assembly, manufacturing, and related terms and technologies.
- Information about future forums for discussion and collaboration.
- Observations on the state of how NASA, DARPA, and other interested agencies are approaching OSAM and the potential set of missions (either collaboratively or separately) with better roadmaps for technology development and needs.
- A plan for a study of the economics of OSAM activities.
- Efforts to establish standards for OSAM activities.
- Identification of key players on both the servicing and client side. Increased collaboration among players, especially support for smaller companies by the government and large primes.
- An understanding of the needs in both industry and government for specific technologies, as well as potential synergistic development opportunities. Sharing of information on current or planned activities for OSAM developments as well as any relevant challenges.
- A reasonable understanding of the timing and means for how various agencies and industry should work together to incrementally develop U.S. OSAM capabilities.
- A productive discussion toward a consistent agreement about the technology development portfolio of the integrated collaboration of government, industry, and academia.
- Agreements on the path forward for government and industry efforts to enable and sustain OSAM activities in the U.S.
- Steps to establish a shared knowledge base, which will enable cooperation in government and commercial efforts to mature technologies and capabilities; this could be supported by the establishment of a routine dialogue among relevant and interested players (e.g., this could provide an opportunity to spread

information about the work and technologies of different entities). Government and commercial efforts to mature technologies and capabilities would benefit from cooperation, thus strengthening this shared knowledge base.

- A coherent U.S. Government system supportive of regulation, policy, licensing of commercial space.

Some respondents hoped steps toward advocacy would follow. Options for this were:

- A path of advocacy for OSAM activities within both the government and industry (e.g., pressure for executive-level direction for space agencies to establish the national lead in OSAM) could help push technologies and efforts forward.
- The workshop could provide recommendations for general OSAM policy as well as outline specific policies and next steps to be examined in the near future.
- Industry and government players could develop an agreement to continue OSAM capability development (both public and private) to encourage the U.S. to lead via sustained technology development and funding.
- Entities could provide a recommendation for a national imperative to fund and develop OSAM for the benefit of U.S. industry, commercial and government missions.
- A discussion should take place assessing the impact of the potential U.S. failure to lead in OSAM capabilities internationally.

18. Are there any additional topics you believe are relevant that have not been covered in the questions above, or anything else you would like to share here?

Additional topics for discussion include:

- The lack of a common vernacular to describe on-orbit activities may complicate future efforts; servicing, assembly, and manufacturing are sometimes used as synonyms, which is incorrect.
- Beyond developing OSAM capabilities, it is necessary to also design future systems that will be able to capitalize on these capabilities. For example, future systems should be designed such that the verification and validation can be performed during in-space assembly, integration, and testing. The potential role of the ISS for OSAM activities (e.g., technology testing and maturation) should be discussed.
- An understanding of the budgets that may be available to support OSAM will allow for insight into the potential of future projects.

- International participation and contributions to U.S. OSAM efforts will be critical. Space is an international environment by nature. The U.S. should foster collaboration with internationals that have similar interests while maintaining global leadership; leading in assembly and manufacturing in space could ensure future U.S. leadership in space.
- International norms of behavior and international SSA/STM warrant more attention. The SSA infrastructure that could be utilized for OSAM logistics and protection remains a question. This includes uncertainty regarding regulation of hazardous operations in key orbit regimes or positions, and which of these future operations need to consider potential clean-up activities in their plans.
- One respondent hoped to address the potential for a disruptive servicing organization for OSAM (e.g., as Amazon does for cloud computing or FedEx does for shipping), rather than traditional aerospace companies providing robotic servicing.

Abbreviations

AI	Artificial Intelligence
AIAA	American Institute of Aeronautics and Astronautics
AST	Office of Commercial Space Transportation
CFIUS	Committee on Foreign Investment in the United States
CONFERS	Consortium for Execution of Rendezvous and Servicing Operations
COTS	Commercial Orbital Transportation Services
DARPA	Defense Advanced Research Projects Agency
DOC	Department of Commerce
DOD	Department of Defense
ECLSS	Environmental Control and Life Support System
EVA	Extravehicular Activity
FAA	Federal Aviation Administration
FCC	Federal Communications Commission
FFRDC	Federally Funded Research and Development Center
GEO	Geostationary Orbit
IC	Intelligence Community
IDA	Institute for Defense Analyses
IP	Intellectual Property
IRAD	Internal Research and Development
ISR	Intelligence, Surveillance, and Reconnaissance
ISRU	In-Situ Resource Utilization
ITAR	International Traffic in Arms Regulations
LEO	Low Earth Orbit
NACA	National Advisory Committee for Aeronautics
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
NRO	National Reconnaissance Office
NSpC	National Space Council
OSAM	On-Orbit Servicing, Assembly, and Manufacturing
OSTP	Office of Science and Technology Policy
PODS	Payload Orbital Delivery System
PNT	Position, Navigation, and Timing
RF	Radio frequency
RPO	Rendezvous and Proximity Operations
RSGS	Robotic Servicing of Geosynchronous Satellites
S&T	Science and Technology
SBIR	Small Business Innovation Research
SPD	Space Policy Directive
SSA	Space Situational Awareness

SSPD	Satellite Servicing Projects Division
STM	Space Traffic Management
STMD	Space Technology Mission Directorate
STPI	Science and Technology Policy Institute
TRL	Technology Readiness Level
UARC	University Affiliated Research Center
USGS	United States Geological Survey
WFIRST	Wide Field Infrared Survey Telescope

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Carioscia, Sara A.
Corbin, Benjamin A.
Lal, Bhavya

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14. ABSTRACT
On May 31, 2018, STPI held a workshop on the challenges, next steps, and roles of government and industry in on-orbit servicing, assembly, and manufacturing. The participants included representatives and subject matter experts from industry and government as well as Federally Funded Research and Development Centers, University Affiliated Research Centers, and universities. This report summarizes the discussion at the roundtable and provides an analysis of responses to a pre-roundtable questionnaire administered to all attendees. The report also offers STPI's recommended next steps to support progress for OSAM activities.

15. SUBJECT TERMS
On-orbit servicing, assembly, and manufacturing (OSAM); payload; Position, Navigation and Timing (PNT); space missions; space situational awareness (SSA); spacecraft

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