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Executive Summary

Background

The space sector is undergoing a major transformation, and there is growing interest in alternative approaches to future space architectures that not only reduce costs but also enhance capabilities in space. Technologies used to closely approach, inspect, grasp, manipulate, modify, repair, refuel, integrate, and build completely new platforms and spacecraft on orbit are viewed as offering direct benefits to a number of fields, including science, space exploration, commercial missions, and national security. As a result, several public, private, and international entities are investing in on-orbit activities, including inspection and servicing of satellites, rendezvous and proximity operations, and robotic assembly and manufacturing. Industry experts have predicted large markets for activities relevant to on-orbit servicing, assembly, and manufacturing. At the same time, the complexity of these operations, concerns about risk, and the lack of international consensus regarding norms of space operations are impediments to their rapid adoption.

Objectives and Approach

Given the perceived importance in the evolving space sector of on-orbit servicing, assembly, and manufacturing, referred to collectively as OSAM, the IDA Science and Technology Policy Institute (STPI) conducted this assessment of global trends in OSAM. We identified the key players currently pursuing or interested in OSAM activities, their countries of origin, the levels of their efforts (technical and financial), their motivations, and planned efforts. We also assessed the potential market and use cases for OSAM, including potential consumer needs and applications, as well as demand from public and private entities. Lastly, we identified, to the extent feasible, global trends in technology, market, and policy relevant to OSAM.

The analysis focuses on activities *outside* the U.S. Government, as well as collaborative efforts to address specific challenges and opportunities related to on-orbit activities and intergovernmental efforts (e.g., those within the European Space Agency). We discuss U.S. activities insofar as they are connected to or support those international and collaborative efforts, or provide context for assessing activities internationally.

The research team conducted over 65 formal interviews with experts from government and industry, spoke informally with selected experts at space conferences and workshops, and reviewed the available literature to identify current OSAM activities internationally and to determine trends in the sector. Using these unclassified data sources, we developed: (1) a model of the OSAM ecosystem consisting of component manufacturers, integrators, operators, funders, and other stakeholders; (2) a database of over 100 international entities actively engaged in one or more OSAM activities; (3) 17 case studies surveying country-specific involvement in OSAM, including information about the country's OSAM landscape, its current and planned activities, key institutions involved, investment and funding mechanisms present, important partnerships, country-specific drivers of its OSAM activities, and barriers to its OSAM activities; (4) a network map of international OSAM partnerships; (5) a mapping from technologies underlying OSAM capabilities to downstream future competencies; and (6) principal drivers of current and future trends in OSAM. Lastly, based on the strengths, speeds, and interconnectivity among the drivers (identified using a Design Structure Matrix approach), we developed 10- to 15-year outlooks on activity in OSAM.

Definitions and Use Cases

The research team defined *servicing* as the on-orbit alteration of a satellite after its initial launch, using another spacecraft to conduct these alterations. Given the breadth of technologies underlying different kinds of services feasible in space, servicing was split into six sub-categories: remote survey (R1), relocation (R2), refueling (R3), repair (R4), replacement of parts (R5), and recharge (R6). We defined *assembly* as the on-orbit aggregation of components to constitute a spacecraft or spacecraft subsystem. Lastly, we defined *manufacturing* as the on-orbit transformation of raw materials into usable spacecraft components. The focus was on manufacturing in space for use in space rather than manufacturing in space for return to Earth.

Within servicing, we identified 11 use cases: remote inspection, ultra-close inspection, orbit change, deorbit/disposal, space debris removal, life extension, refuel, repair, upgrade, remote recharge, and contact recharge. Within assembly, we identified three use cases: satellite enhancement, persistent platform, and space telescope. Within manufacturing, we identified four use cases: basic manufacturing, advanced manufacturing, in-situ resource utilization, and recycling.

Technology Areas Evaluated

To estimate OSAM capabilities in the next 10–15 years, the research team began by identifying technology areas that are critical, desirable, or enabling for OSAM services, and then attempted to evaluate the state-of-the-art in each by country of interest. Technologies such as propulsion or guidance and navigation are important for almost all OSAM capabilities; others, such as wireless power transfer, may only apply to one or two use cases. Rendezvous and proximity operations are prerequisites for all servicing activities, as well as for most major assembly and manufacturing activities (Figures ES-1 and ES-2).

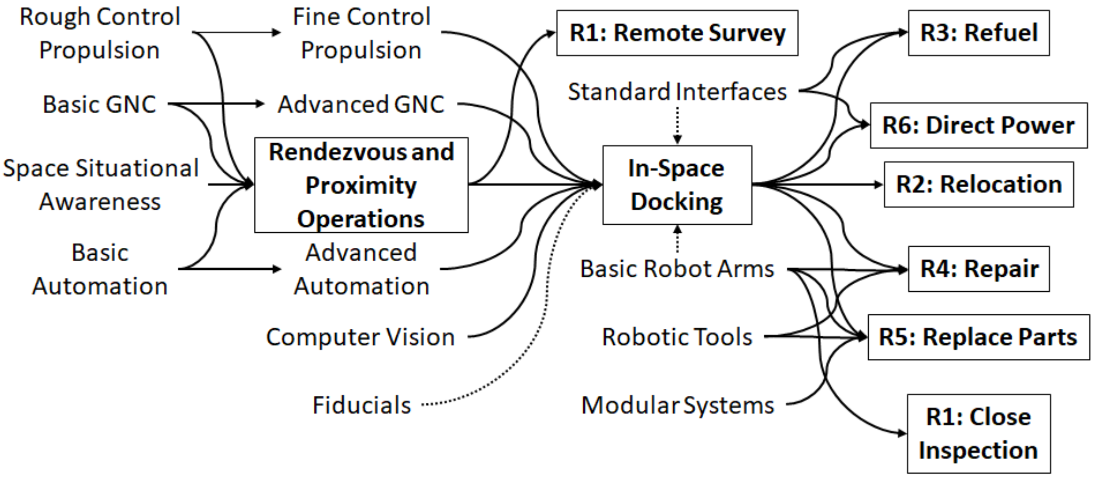


Figure ES-1. Technologies Required for On-Orbit Servicing

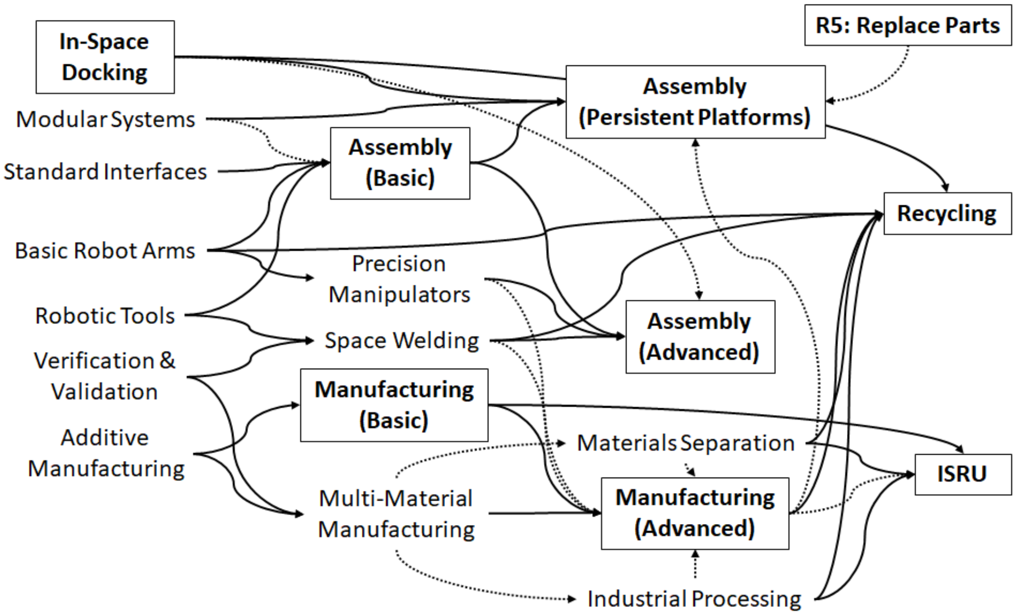


Figure ES-2. Technologies Required for On-Orbit Assembly and Manufacturing

Global Activities in Areas of Interest

The STPI team identified more than 100 organizations engaged in OSAM-related technology development in 17 countries or regions around the world (Figure ES-3). Of the 17, nine have significant activities in one or more areas of OSAM. Table ES-1 shows the United States has the widest range of OSAM activities, closely followed by Russia and China. Some countries, such as Germany, have or are rapidly developing the underlying technologies required for OSAM, but are not yet actively pursuing or leading OSAM missions. Other countries such as Japan have concentrated on specific use cases such as relocation and debris removal.

Source: STPI Database

Figure ES-3. Distribution of OSAM Organizations by Country and Region

We observed two broad policy-related trends in OSAM. First, we noted that some space agencies are working towards nurturing business environments where the private sector can grow and promote the progression of OSAM through collaboration with the government (e.g., Luxembourg, the United Kingdom, and the United States). Other countries' OSAM-related activities are largely or entirely government-driven (e.g., China and Russia). Second, we noted that no countries in our dataset have national level OSAM policies, though about a half dozen countries have plans to develop them.

While there is no global coordination of OSAM-relevant policies or regulations, there is an international push towards the establishment of standards; multinational groups and consortia are leading the way on a conversation on regulations and standards. We were able to identify three such organizations: the U.S.-led but internationally-oriented Consortium for Execution of Rendezvous and Servicing Operations (CONFERS) that is currently funded by DARPA but is eventually expected to be member-funded; the European Union funded and Europe focused PERASPERA; and the industry-led and safety and sustainability-focused Space Safety Coalition.

Table ES-1. Level of Country OSAM Capability by Country and Region

OSAM Use Cases	US	CN	RU	JP	DE	UK	EU	CA	AU
R1: Remote Inspection	3	3	3	2	2	2	2	2	3
R1: Close Inspection	3	2	2	2	2	2	2	2	0
R2: Orbit Maintenance	3	2	2	2	2	2	2	2	0
R2: Orbit Transfer	3	2	2	2	2	2	2	2	0
R2: Deorbit	3	2	2	2	2	2	2	2	0
R3: Refuel	3	3		0	2	2	2	2	0
R4: Repair	2	1	1	1	2	1	2	2	0
R5: Replace Parts	2	1	1	1	2	1	2	2	0
R6: Power Beaming			2						
R6: Solar Reflection	1	1				1			0
R6: Direct Power	2	2	2	1	2		2	2	0
A: Basic	3	2	3	3	2	1	2	3	0
A: Precision	1	0	0	0	0	0	0	1	0
A: Platforms	2	1	2	1	2	1	2	2	0
M: Basic	3	2	3		0				1
M: Advanced	1		1		0				0
M: ISRU	1	1	1	1	1	1	1	0	1
M: Recycling	1				0				0

Table Key:

0: This country is missing more than one critical technology and will not likely be engaging in this activity soon

1: This country is not yet capable, but has some advancement in the main critical technologies and has invested in the application

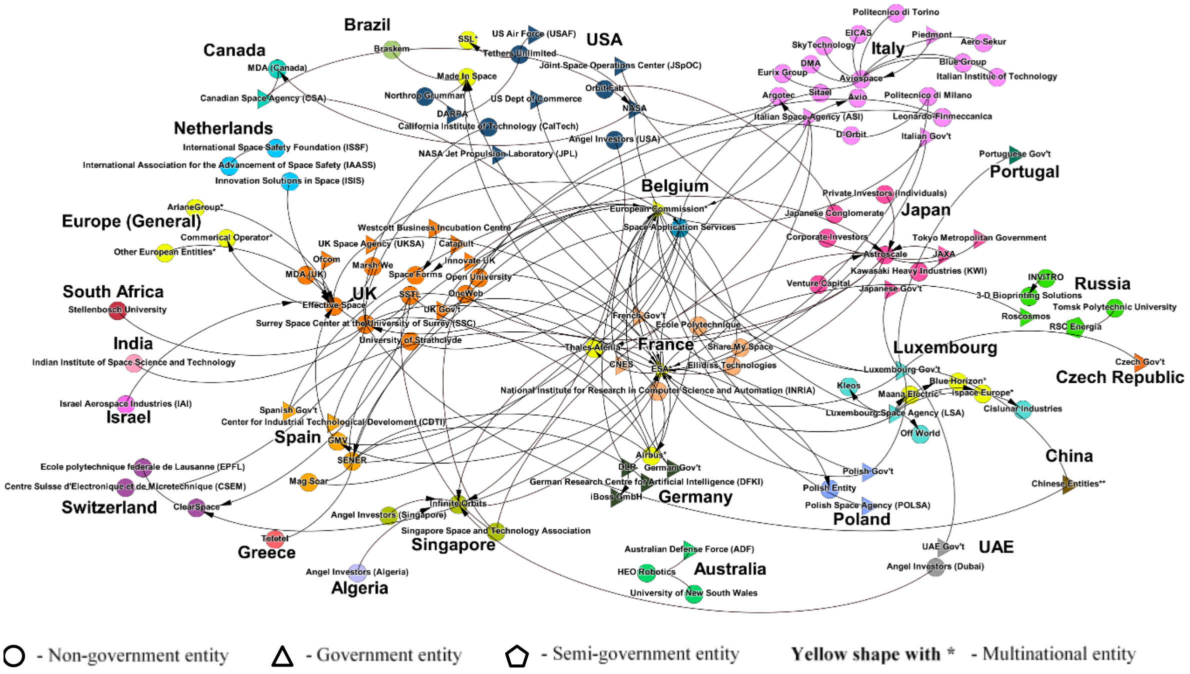
2: This country has all of the technology prerequisites (or at least the most important ones) and could be capable within 5 years with minor effort

3: This country is already engaged in some form of this application

Blank: It is unclear what this country’s current capability is in this activity

Abbreviations: US: United States. CN: China. RU: Russia. JP: Japan. DE: Germany. UK: United Kingdom. EU: European Union. CA: Canada, AU: Australia.

Beyond these consortia, we identified more than 100 entities in 26 countries engaged in over 150 partnerships (Figure ES-4). Most of the countries involved in OSAM partnerships are European, though the United States appears well integrated into the OSAM partnerships internationally. While China and Russia are not as integrated into international OSAM partnerships, both have collaborated with important players. Many countries on the fringe of the OSAM landscape—such as Algeria, Greece, India, and the United Arab Emirates—participate by means of their academic institutions, angel investors, or governments.



Notes: Not all U.S. entities engaged in OSAM are included given that this graphic aims to visualize non-U.S. partnerships. Additionally, the partnerships between CONFERS and PERASPERA members are not included.

** - See the China case study in Appendix C for more details on entities and domestic activities in China

Figure ES-4. Network Map of International (Non-U.S./U.S.) OSAM Partnerships

Drivers of OSAM and Future Trends

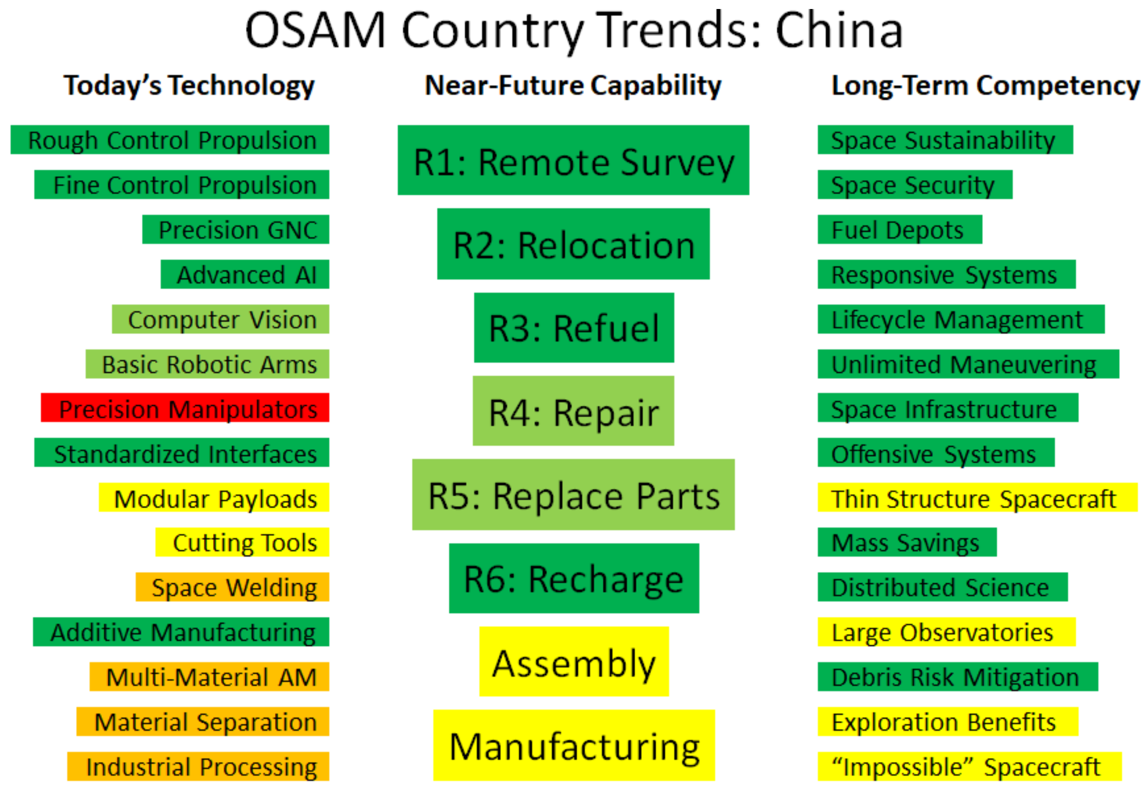
In all the countries of interest, STPI researchers identified more than 50 unique drivers of OSAM that fall into six categories: technology; government programs; commercial markets; infrastructure and architecture; policy; and discrete events. Our analysis found that seven of these drivers have the most influence in shaping the development and adoption of OSAM technologies in space (Table ES-2). Many of these drivers have second- and third-order impacts on OSAM's future with regard to their interconnectivity with other drivers. For example, the falling cost of launch can help prove out OSAM technologies but also make it cheaper to launch replacement satellites rather than repair them.

Table ES-2. Key Drivers in the OSAM Ecosystem

Driver	Rationale
Advances in basic component technologies (+)	Influences all OSAM capabilities and use cases
Cost of launch, particularly the cost of heavy launch (+/-)	Complex effect—lower launch costs can help prove out OSAM technologies but also make it cheaper to launch replacement satellites rather than repair them
Development of standards (+)	Standards establish norms for operations, but also ensure OSAM is less risky and better understood
Government regulations (+/-)	Restrictions can make or break the case for OSAM—mostly affect refueling and relocation services
Government decisions on missions/architectures (+/-)	Government is a reliable customer (if it chooses architectures that can benefit from OSAM), can build investor confidence
Demand for communications services (+/-)	Growth in space-based communications, if in LEO, may increase the need for deorbit services. If in GEO, it may drive the case for other OSAM services (repair, replace parts, assembly). However, there will be a negative effect if terrestrial services vastly outperform space services.
Investor confidence/venture capital (+)	Driven by other drivers, and also a strong driver of all commercial OSAM activities and technologies

Extrapolating out from these drivers systematically shows that given the uncertainties involved in OSAM operations, the technological risks involved with such activities, the current configurations of satellites on orbit today, and the difficulty in articulating the long-term value proposition of some higher-order competencies, the adoption rate of OSAM activities will likely be variable across different use cases—faster in some such as remote inspection, and slower in others such as refueling. In the next 10–15 years, while some OSAM operations such as relocation, life extension, or remote survey will become common, OSAM as a whole may not see the explosive growth of other recent developments such as small satellites or the small launch vehicle market. In our timeframe of interest, while private users may be few, government use—in national security or space science—of OSAM services could grow faster depending on the nature of future operations in space. On the policy front, while it is unlikely that a coordinated international OSAM policy or guidelines would be established, the international community could make progress in developing bottom-up standards. A significant collision in space could serve as an impetus for OSAM policy and regulations both within countries or internationally.

Overlaying our understanding of the current state of technology and investment, the drivers that affect OSAM, and published national strategies (where available), STPI researchers assessed the current technology readiness of six countries we deem the most relevant, projected the *capabilities* they could have in the near-future (3–5 years), and forecasted downstream *competencies* they could acquire within the next 15 years. We found that China and Russia are closest to the United States with respect to not just technology maturity of component technologies, but also current OSAM capabilities; both countries could have similar future competencies to the United States if they continue to pursue OSAM at their current levels of effort. Figures ES-5, ES-6, and ES-7 summarize this assessment.



OSAM Country Trends: China

Today's Technology

- Rough Control Propulsion
- Fine Control Propulsion
- Precision GNC
- Advanced AI
- Computer Vision
- Basic Robotic Arms
- Precision Manipulators
- Standardized Interfaces
- Modular Payloads
- Cutting Tools
- Space Welding
- Additive Manufacturing
- Multi-Material AM
- Material Separation
- Industrial Processing

Near-Future Capability

- R1: Remote Survey
- R2: Relocation
- R3: Refuel
- R4: Repair
- R5: Replace Parts
- R6: Recharge
- Assembly
- Manufacturing

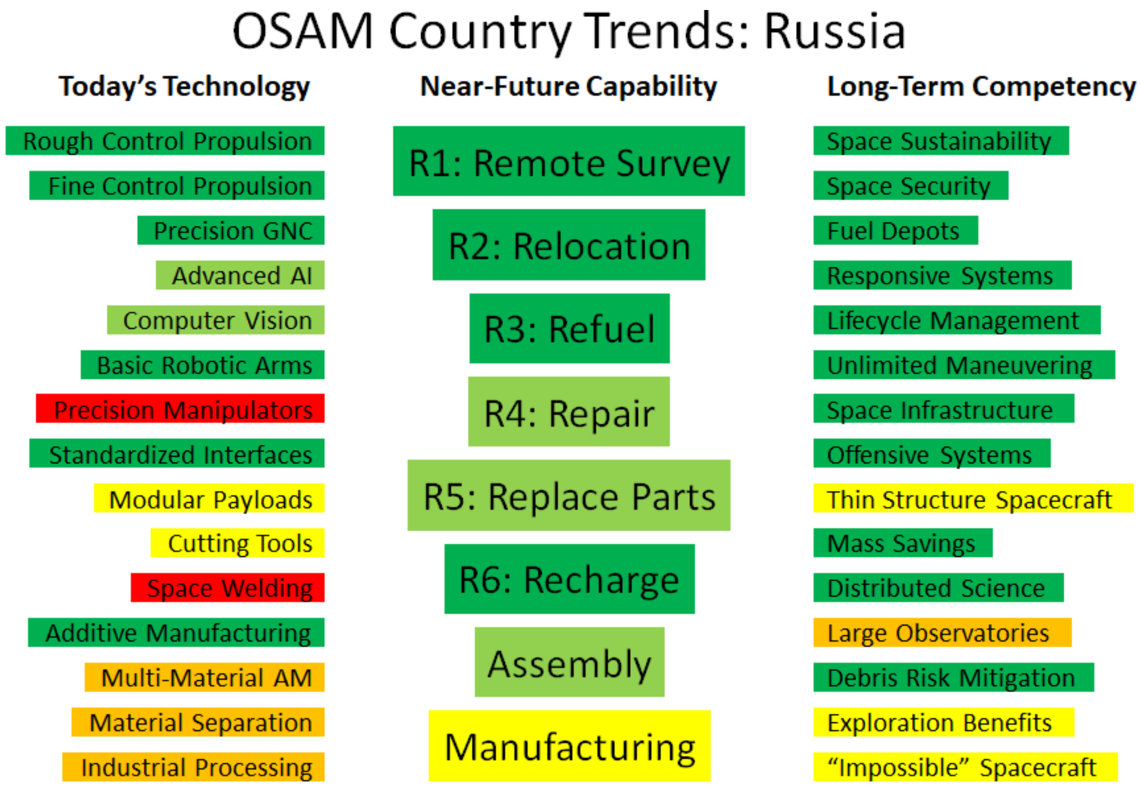
Long-Term Competency

- Space Sustainability
- Space Security
- Fuel Depots
- Responsive Systems
- Lifecycle Management
- Unlimited Maneuvering
- Space Infrastructure
- Offensive Systems
- Thin Structure Spacecraft
- Mass Savings
- Distributed Science
- Large Observatories
- Debris Risk Mitigation
- Exploration Benefits
- "Impossible" Spacecraft

Note: The color scale has different meanings in each column:

- Today's Technology:
  - Green: The country has already used this technology in this application
  - Light Green: The country has demonstrated this technology for this application
  - Yellow: The country is actively working towards this technology
  - Orange: The country has announced plans or has made some progress in this technology
  - Red: The country does not have nor are they pursuing this technology
- Near-Future Capability and Long-Term Competency:
  - Green: Very likely this country will have capability within 5 years/competency within 15 years
  - Light Green: Likely this country will have capability within 5 years/competency within 15 years
  - Yellow: Somewhat likely this country will have capability within 5 years/competency within 15 years
  - Orange: Unlikely this country will have capability within 5 years/competency within 15 years
  - Red: Very unlikely this country will have capability within 5 years/competency within 15 years

Figure ES-5. Assessing Ability to Acquire Future Competencies: China



OSAM Country Trends: Russia

Today's Technology

- Rough Control Propulsion
- Fine Control Propulsion
- Precision GNC
- Advanced AI
- Computer Vision
- Basic Robotic Arms
- Precision Manipulators
- Standardized Interfaces
- Modular Payloads
- Cutting Tools
- Space Welding
- Additive Manufacturing
- Multi-Material AM
- Material Separation
- Industrial Processing

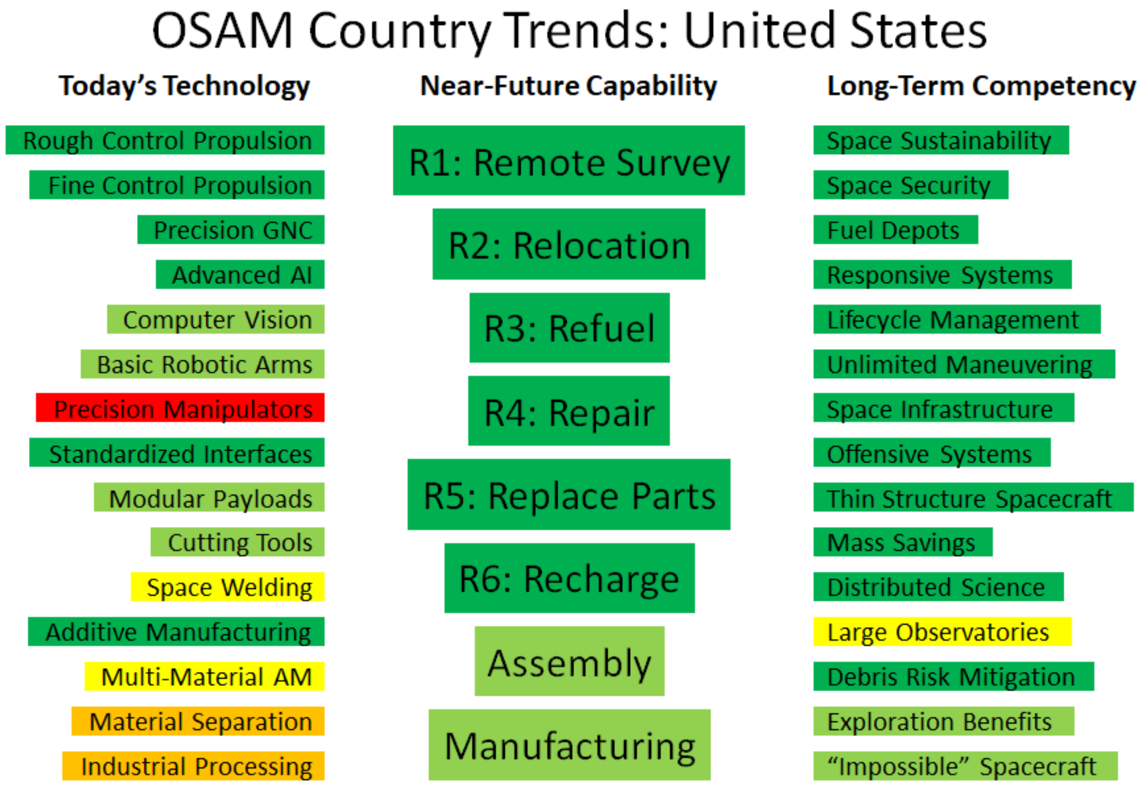
Near-Future Capability

- R1: Remote Survey
- R2: Relocation
- R3: Refuel
- R4: Repair
- R5: Replace Parts
- R6: Recharge
- Assembly
- Manufacturing

Long-Term Competency

- Space Sustainability
- Space Security
- Fuel Depots
- Responsive Systems
- Lifecycle Management
- Unlimited Maneuvering
- Space Infrastructure
- Offensive Systems
- Thin Structure Spacecraft
- Mass Savings
- Distributed Science
- Large Observatories
- Debris Risk Mitigation
- Exploration Benefits
- "Impossible" Spacecraft

Figure ES-6. Assessing Ability to Acquire Future Competencies: Russia



OSAM Country Trends: United States

Today's Technology

- Rough Control Propulsion
- Fine Control Propulsion
- Precision GNC
- Advanced AI
- Computer Vision
- Basic Robotic Arms
- Precision Manipulators
- Standardized Interfaces
- Modular Payloads
- Cutting Tools
- Space Welding
- Additive Manufacturing
- Multi-Material AM
- Material Separation
- Industrial Processing

Near-Future Capability

- R1: Remote Survey
- R2: Relocation
- R3: Refuel
- R4: Repair
- R5: Replace Parts
- R6: Recharge
- Assembly
- Manufacturing

Long-Term Competency

- Space Sustainability
- Space Security
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- Large Observatories
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Figure ES-7. Assessing Ability to Acquire Future Competencies: United States

Contents

1. Introduction

A. Background

The space sector is undergoing a major transformation, enabled by decreased development costs and advances in space technologies and technologies in adjacent sectors. Private and government actors from more and more countries are participating in an ever-increasing number of activities in space; global interest in the sector continues to increase (Lal et al. 2015). Despite these technical advances and the growth in the number of global actors engaged in increasingly sophisticated activities in space, spacecraft design and system architectures remain the same as at the start of the space age, and are still constrained by the limitations associated with assembly and integration on Earth (Boyd et al. 2016; Carioscia et al. 2018).

Increasingly, however, entities operating in space are realizing that manufacturing and launching fully-built spacecraft that are expected to function flawlessly at their full capacity for decades away from Earth imposes significant limitations on the size, volume, and design of spacecraft. The conundrum of traditional spacecraft design is as follows: the capacity and volume of the launch vehicle restricts the mass, size and number of instruments that can be included; components must be made very rugged to withstand the harsh launch environment, which imposes mass and size penalties that limit payload capabilities and increases complexity, test time, and cost. Making spacecraft and instruments rugged is only required for the first 8 minutes of their lives, not the remaining decade or more of normal operations; some spacecraft and components, such as ultra-thin mirrors and gossamer structures cannot be built on Earth at all, thereby limiting their range of capabilities in space. Backups and redundancies must be included to provide contingencies against damage during launch or failure on orbit; once an asset is in space, it typically cannot be refreshed or improved. To date, opportunities to increase the flexibility, capability, and resilience of space assets (i.e., through payload additions, replacements, and technology updates while on orbit) have been limited.

Given the physical and technical limitations imposed by assembly and integration on Earth, as well as the need and opportunity to continually update and refresh assets after launch into space, globally the space industry is exploring new approaches where current and future space objects can be serviced on orbit, and future space objects can be partially or wholly assembled or manufactured in space. Experts believe that "the ability to approach, inspect, grasp, manipulate, modify, repair, refuel, integrate, and build completely new platforms and spacecraft on orbit would enable new business models, innovation, and opportunities in space" (Barnhart et al. 2018). These technologies offer direct benefits (i.e., reduced cost, reduced time of assembly and testing on the ground, increased resilience, and increased capability) to a number of fields, including science (astronomy, Earth science, solar and space physics), exploration, commercial missions, and national security (Boyd et al. 2016). As a result, several public, private, and international entities are beginning to engage in on-orbit activities, including inspection and servicing of satellites, rendezvous and proximity operations, and robotic assembly and manufacturing. Industry experts have predicted large markets for on-orbit servicing, assembly and manufacturing (OSAM) relevant activities; for example, Northern Sky Research has forecast that over $3 billion in cumulative revenues will be generated by 2029 from applications such as satellite life extension, relocation, deorbiting, salvage, robotics, and space situational awareness (NSR 2020).

While on-orbit activities have the potential for significant civil and commercial applications, they can also threaten assets and activities in space—including those of the United States when on-orbit activities are conducted by state-owned and private actors of other nations. The importance of understanding "the scope, degree, and diversity of the threats facing future use of space" has been emphasized by several national security experts in space activities (Weeden 2018). In order to identify and understand these threats, it is essential to first understand the motivations of the players, the technologies involved and their maturity levels, as well as ongoing challenges related both to technology development and the surrounding policy framework.

B. Objectives

Given its importance in the evolving space sector, in July 2019, the IDA Science and Technology Policy Institute (STPI) began an assessment of global trends in on-orbit activities, with focus on in-space servicing, assembly and manufacturing. The goals of the study were to identify the key players currently pursuing or interested in on-orbit activities, their countries of origin, the levels of their efforts (technical and financial), their motivations, and current and planned efforts. We also aimed to conduct a basic assessment of the potential market and use cases for on-orbit activities, including potential consumer needs and applications, as well as demand from public and private entities in space. This assessment was to be informed by an analysis and projection of the challenges faced by organizations pursuing on-orbit activities, including issues with regulations, licensing, and policies; technological advances and difficulties; and international agreements and collaborations.

Building on this data collection effort, STPI strove to identify and predict, to the extent feasible, global trends in technologies, markets, and policies that are relevant to on-orbit activities. We considered the current technological maturity and funding levels of both private and public endeavors, the applicability and progress of relevant policies and regulations, and the potential for new entrants, technological developments, international conflicts, synergistic effects of technology interactions, and other external events to influence the area.

The scope of the report constrained the analysis to global activities *outside* the United States, including collaborative efforts to address specific challenges and opportunities related to on-orbit activities and intergovernmental efforts (e.g., those within the European Space Agency). The analysis discusses U.S. entities insofar as they are connected to or support those international and collaborative efforts.

We addressed the goals of the study at two levels: understanding OSAM capabilities and technology needs independent of where the activities are occurring, and country-level activities. For the first analysis, the following questions were posed:

- How is OSAM defined? What are the elements and technologies involved in OSAM?
- What OSAM capabilities are feasible in the next 10–15 years? If these capabilities are achieved, what can OSAM enable that was not possible before (either because it was impossible, too expensive, or did not make sense operationally)?
- What factors (e.g., demand for services, regulations, government funding, big-picture space priorities and space architecture decisions, debris events in low Earth orbit [LEO]) may accelerate progress in reaching the goals of OSAM? What factors (e.g., regulations, lack of demand) may hold back progress?
- What are some of the other consequences or effects that change the nature of space operations as a result of OSAM capabilities (e.g., decreased need for heavy lift launchers, or a stronger market for small launch vehicles) in the next 10–15 years?

For country-level analyses, the following questions were posed:

- Which countries are actively involved in OSAM? In what OSAM development activities are they engaged?
- What capabilities are they aiming for and over what timeline? How (if at all) do countries' OSAM activities fit with their bigger-picture space and country priorities?
- How much are these countries currently spending on or plan to spend on their OSAM priorities? How is this spending likely to change in the next decade? How much of the funding is from governments and how much comes from the private sector?

- What partnerships exist (or are planned)? Between whom? For what purpose? What gaps can these partnerships fill? How globalized (as distinct from closed-off in-country) is OSAM as a sector?
- What country-specific factors may accelerate or derail their visions for development/use of OSAM?

Questions at both levels were turned into interview protocols. The interview protocols are included in Appendix B.

C. Methodology

1. Definitions

The focus of the report is on on-orbit servicing, assembly and manufacturing (referred to as OSAM throughout the report). For the purposes of the report, this is how each element of OSAM was defined:

- Servicing was defined as the on-orbit alteration of a satellite after its initial launch, using another spacecraft to conduct these alterations. Servicing includes at least the following six specific activities.
    - Remote Survey: close or ultra-close inspection of a spacecraft or satellite
    - Relocation: moving the spacecraft, which includes orbit maintenance, modification, and transportation
    - Refuel: adding propellant, which includes transfer of fluids from one spacecraft to another
    - Repair: fixing spacecraft, which includes activities such as untangling deployable systems or realigning optics
    - Replace Parts: change out parts of a spacecraft, possibly as an upgrade
    - Recharge: delivering electric power to a spacecraft, remotely or through a physical connection
- Assembly involves the on-orbit aggregation of components to constitute a spacecraft or spacecraft subsystem.
- Manufacturing involves the on-orbit transformation of raw materials into usable spacecraft components. The study focused on manufacturing in space for use in space rather than manufacturing in space for return to Earth (i.e., we included efforts to use the resources of space, but not efforts to manufacture products that will be sent back to Earth).

2. Data Collection and Analysis

After determining the scope of the study and developing the project's study questions, the STPI team conducted over 65 interviews with experts from government and industry; spoke with representatives at space conferences and workshops; and reviewed over 300 articles, papers, and reports to understand current OSAM activities internationally, and assess trends in the sector. All data collection was conducted at the unclassified level.

Based on the data collected, the STPI team developed:

- A structural model of the OSAM ecosystem that consists of component manufacturers, integrators, operators, users, funders, and providers of other services relevant to OSAM
- A database of over 100 international entities actively engaged in each of the following OSAM activities: remote surveillance (R1), relocation (R2), refueling (R3), repair (R4), replacement of parts (R5), recharge (R6), assembly (A), and manufacturing (M)
- 17 country or regional case studies surveying country-specific involvement in OSAM, including information about the country's OSAM landscape, its current and planned activities, key institutions involved, investment and funding mechanisms present, important partnerships, drivers of its OSAM activities, and barriers to its OSAM activities as well as case studies of multilateral organizations such as the European Union
- A network map of international OSAM partnerships visualizing relationships in the global sector that visually illustrates how entities interact with one another
- A mapping from technologies underlying OSAM capabilities to downstream future competencies

To better characterize potentially competing relationships between drivers of OSAM, STPI used an approach called the design structure matrix (DSM) to qualitatively assess dependencies across elements of the OSAM capability space. The approach helped identify the most important drivers of developments in OSAM, as well as the interdependencies and sensitivities among the drivers.

D. Organization of the Report

The remainder of this report is organized as follows. In Chapter 2, we describe the elements and technologies encompassed by OSAM and the capabilities it can enable if successful. Chapter 3 reiterates the presumed value proposition of OSAM—we examine several OSAM use case scenarios and why, despite clear advantages for OSAM use, it is still difficult to adopt OSAM capabilities for missions, both government and private.

Chapter 4 focuses on understanding existing global activity in OSAM. We offer descriptive statistics that summarize ongoing global activity, analyze global activities in each component of OSAM, examine the state of technology by country, dissect the landscape of international partnerships through a network diagram, and look at the status of policy and regulations.

Chapter 5 builds on the previous chapters by identifying the drivers that could accelerate or inhibit the development of OSAM technologies. Chapter 6 concludes our report and offers our projection of where OSAM could be in the next 10–15 years. Appendices A–E provide supporting documentation:

- Appendix A lists names and affiliations of interviewees who agreed to be listed.
- Appendix B reproduces the protocols used for our discussions with experts.
- Appendix C includes the country and regional case studies of OSAM activities.
- Appendix D outlines the status of OSAM policy in 15 countries based on background research and interviews.
- Appendix E describes the methodology behind the design structure matrix used to understand how drivers influence OSAM's development.

2. OSAM Capabilities and Technologies

This chapter addresses the first study question: What is OSAM, and what are the elements and technologies involved in it?[1] We begin by defining each element, describing the technologies or operations required to successfully pursue each element, and discussing their potential to enable capabilities if the technologies and operations come to fruition.

A. On-Orbit Servicing

As introduced above, on-orbit servicing is defined as the on-orbit alteration of a client spacecraft or satellite after its initial launch, using another servicing spacecraft or system to conduct these alterations. It is a collective term that includes a number of actions such as orbit modification, replenishment of on-board consumable resources, and hardware maintenance, all of which are carried out in orbit. STPI has organized the range of activities into a taxonomy called the "six Rs" that builds on previous NASA efforts to define satellite servicing.[2] Each is described below.

1. R1: Remote Survey

a. What is Remote Survey?

When a satellite is not performing nominally or as planned, it can be useful to examine its exterior for signs of damage or mechanism malfunction. Even if the satellite is performing more or less as it should, imagery can be useful to operators and engineers. The quality of images obtained from ground-based telescopes and radar is insufficient for most desired diagnoses; also, a satellite may not be oriented properly for ground-based telescopes to see the affected exterior component. Images taken from a nearby satellite equipped with the appropriate cameras can supply the required quality and image the desired aspect of the satellite.

There are two levels of service associated with this capability. An inspector satellite several kilometers from the subject spacecraft can obtain imagery of sufficient detail to

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[1] There is debate in the community over whether it should be OSAM or ISAM—In space Servicing, Assembly, and Manufacturing—as OSAM implies restriction to Earth orbit and would not include lunar or deep space activities. For purposes of this report, we are primarily focused on on-orbit activities but do not exclude developments for further activities.

[2] NASA has used the term "Five Rs" (Weeden et al. 2013). Based on our research, STPI has added a sixth element—R6: Recharge.

identify the source of a problem—such as an antenna or solar panel that has deployed improperly, or an insulating blanket that came loose during launch. However, such images may not provide sufficient detail to understand the specific cause of a malfunction. To obtain ultra-close imagery, it would be unsafe to operate a free-flying satellite very close to another spacecraft. Instead, an inspector satellite would first dock with the subject and use arm-mounted cameras to obtain images a few inches to feet from suspect mechanisms, including areas that were partially obscured from view.

Satellites intended for other space servicing missions, such as life extension, are also capable of providing remote imaging services.

b. Why Conduct Remote Survey?

Today, inspection data is most relevant for improving satellite designs and for insurance adjustment. Servicing satellites such as DARPA’s Robotic Servicing of Geosynchronous Satellites (RSGS) vehicle will soon be arriving in geosynchronous Earth orbit (GEO) (Roesler 2017). RSGS is equipped to perform ultra-close inspection; however, it can also apply calibrated mechanical forces to assist with malfunctioning deployment mechanisms. In the future, remote and ultra-close images may be important in support of a decision to contract for a repair mission by a servicing satellite. Repairs are of very high economic value, as they restore a capability years before a replacement could be launched, and a repair could eliminate the need for an insurance claim.

Remote surveys have been identified as crucial for improved satellite design. For example, one satellite manufacturer had its GEO satellites exhibit the same solar array deployment failure mode in multiple iterations: 2004, 2012, and 2013. In each case, post-anomaly analysis suggested design changes that should have precluded repeat failures, but the analysis was flawed. Remote survey or ultra-close inspection could have yielded information to improve the anomaly analysis.

Remote surveys can also help the insurance industry adjust payouts. Between 2004 and 2014, for example, there were five deployment failures among commercial GEO satellites. The average insurance payout per event was $130 million. Detailed diagnostic imagery might have allowed the underwriters to adjust their premiums based on proposed design changes, improving their margins against future claims. A recent case of a deployment anomaly occurred in 2018 onboard Viasat-2. Designed for a throughput of 350 billion bits per second (Gbps), the spacecraft was only achieving 260 Gbps. An antenna deployment issue was suspected, but no in-space imagery was available. An insurance claim of $188 million was paid.

Imaging of military satellites that have experienced anomalies can have the same benefits as with commercial satellites. Military satellite operators have two additional motivations to obtain close or ultra-close imagery: obtaining evidence of hostile action, and intelligence gathering. If a military satellite experiences an unanticipated outage, the causes could include engineering flaws, natural phenomena (solar storms or micrometeoroid damage), or hostile action by an adversary nation. Resolving these possibilities would be of strategic importance to national authorities. As an example, in 2008, the infrared early warning satellite DSP-23 suddenly failed. This occurred shortly after China destroyed one of its own satellites with an anti-satellite weapon. While hostile action was considered an unlikely cause of the DSP-23 failure, it could not be discounted. No sources of imagery were available to resolve the mode of failure, which remains unresolved today.

Close-range imaging of the satellites of other nations can help to identify threat capabilities that would otherwise remain unknown. The governments of the United States, Russia, and China are known to have these capabilities. The U.S. Geosynchronous Space Situational Awareness Program (GSSAP), for example, provides close imaging capability in the near geosynchronous orbit regime. The four known GSSAP satellites to-date have the capability to perform rendezvous and proximity operations (RPO), which allows them to maneuver near an object of interest and characterize it for enhanced surveillance and other purposes (Hitchens 2019b; U.S. Air Force 2017).

2. R2: Relocate

a. What is Relocation?

Most satellites must maintain their orbit precisely to perform their missions, whether commercial or military. To do this, they are equipped with propulsion systems. They are launched with the amount of fuel calculated to enable them to maintain orbit throughout their design lifetimes. Orbit maintenance is required because of drag (in LEO) and the influence of the Moon's gravity and radiation pressure from the Sun (in GEO). In large LEO constellations—such as that of Iridium with 66 satellites or SpaceX, which expects to have many thousands of satellites—orbit maintenance is also important to maintain the relative spacing of satellites. In GEO, positions along the equatorial orbit are allocated in 1-degree increments (760-kilometer arc lengths), but positions are typically maintained at the center 0.1-degree of those increments.

Relocation and orbit modification are performed by a space servicing vehicle attaching to its client, using the servicer's propulsion to move the client to a different orbit. Most current systems target GEO relocation, because of the large number of high-revenue potential clients in the single orbit. One type of relocation service would be to move a GEO satellite from one 1-degree slot to another. Another service would be to move an end-of-life GEO satellite from its slot to the disposal or "graveyard" orbit 300 kilometers above GEO altitude.

Relocation and orbit modification could also be an approach to space debris removal. To remove a large object from orbit that is no longer responding to commands, a propulsive vehicle would attach to it and perform a maneuver to reduce the orbit perigee (closest approach to the Earth) to be within the atmosphere. The drag from passing through the atmosphere will either lower the apogee (farthest point from the Earth) or will heat the object enough to destroy it. After the maneuver, the propulsive vehicle could perform another maneuver to raise its perigee back and save itself to conduct more missions, if it had sufficient propellant.

Satellites intended for other space servicing missions, such as life extension, are also capable of providing relocation and orbit modification services.

b. Why Conduct Relocation?

A typical GEO communications satellite earns about $40 million per year for its operator.[3] The operator is required to dispose of the satellite (raise its altitude to the graveyard orbit) before it becomes inoperable. Failure to do so may result in the operator losing its license for the GEO position, a severe economic penalty. Thus, the operator will be sure to dispose of the satellite when it still has enough fuel for the disposal maneuver.

If a servicing vehicle were able to dispose of the client satellite after it exhausted its propellant, the operator would have achieved maximum economic return from its satellite. Such missions can be preplanned years in advance, an advantage to the client operator from a fleet maintenance perspective, and also to the servicer, so it can optimally schedule servicing missions.[4]

Relocation is also one approach to extending the life of a satellite (Galabova 2006), the other way being refueling (next section). By extending the life of a satellite, the capital expenditure required for its replacement can be deferred. Relocation and orbit modification might also be of value for responding to a crisis in space. Relocation may frustrate an adversary’s offensive space plans. Removal of damaged satellites following a conflict in space may restore the space environment to its relatively hazard-free pre-conflict state.

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[3] Based on estimates from 2019 fiscal reports from four of the top commercial communications satellite companies. Per satellite, SES earned $41.9 million (SES 2020), Intelsat earned $34.9 million (Intelsat 2020), Eutelsat earned $37.8 million (Eutelsat 2020), and Telesat earned $49.8 million (Telesat 2020).

[4] Intelsat is expected to pay Northrop Grumman $13 million per year for the time MEV is attached to its satellite ($65 million total). For reference, the satellite probably cost about $300 million to build, and about $100 million to launch. Source: https://www.fool.com/investing/2019/10/13/northrop-grummans-space-tow-truck-has-finally-arri.aspx

3. R3: Refuel

a. What is Refueling?

Propellant expenditure is often a limiting factor in the operating times of satellites. For commercial GEO satellites, it has been estimated that over half of satellites are sent to the disposal orbit solely because of propellant exhaustion, even when all other systems are functioning nominally (Benedict 2016). Extending the life of such a late-in-life but still functional satellite can result in additional revenues for its operator, and can provide benefits in terms of fleet flexibility and capital expenditure.

The life of a satellite can be extended in two ways: by adding propellant to its tanks or by attaching another vehicle that provides orbit maintenance with its own thrusters (an instance of relocation, previous section). Addition of propellant requires complex robotic operations: the servicer must dock with the client, and access the fill and drain valves used to fuel the client just prior to launch. A fueling hose is attached, probably including a leave-behind safety valve. Fuel is transferred, then the system is closed out, including replacing any displaced insulation.

b. Why Conduct Refueling?

As mentioned above, a typical GEO communications satellite earns about $40 million per year for its operator, with the value of the data at $400 million to over $1 billion per year if other users are included. If a servicing vehicle were able to give a client satellite more propellant, the operator would be able to achieve additional economic return from its satellite. Similarly, contracting for the services of a mission extension vehicle extracts additional useful life from the satellite. Some studies have indicated that the economic returns for refueling could be strong, both for the servicer operator and for the client (Benedict 2014).

There is an additional economic benefit to the GEO operator from this service. By extending the life of a satellite, the capital expenditure required for its replacement can be deferred, assuming that the satellite is still producing ample revenues.

While most refueling and life extension concepts today are targeted at GEO clients, the technologies are also applicable to LEO. However, because more delta-V is required to move between orbits in LEO compared to GEO, the diversity of LEO orbits means that a servicer today would likely be unable to reach multiple clients economically. In the future, if certain “preferred” LEO orbits include servicers, clients needing refueling over their lifetimes would populate those orbits preferentially.

Military satellites tend to cost much more than commercial ones. A typical commercial GEO communications satellite costs $300 million. Recent U.S. Air Force satellite purchases have included WGS ($560 million each), Advanced EHF ($1.2–$1.4

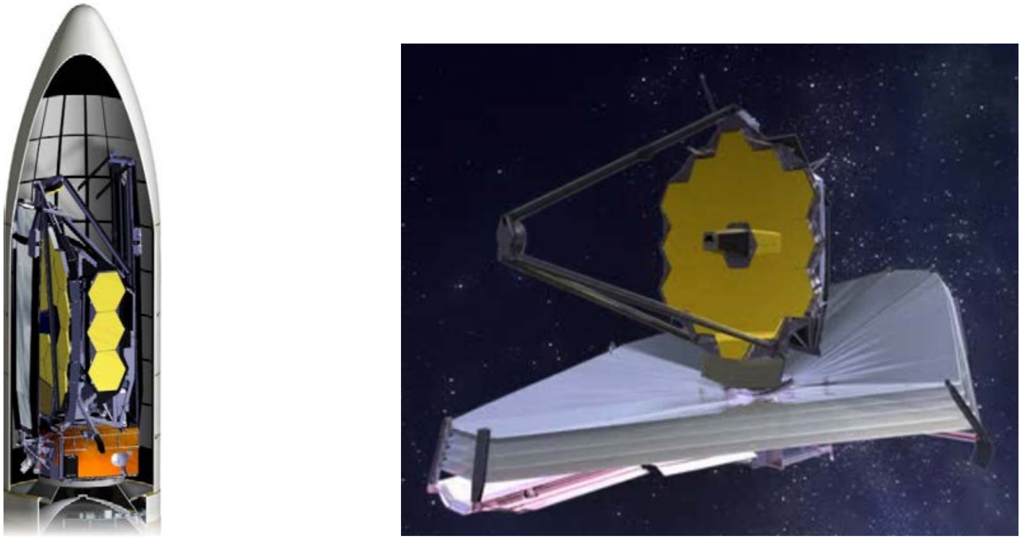
billion), and SBIRS ($1.4–$4 billion). Extending the lives of these very expensive satellites is of even higher value than for commercial ones, although given the speed of technological development, governments often prefer to upgrade satellites rather than extend their lives.

Military satellites may also be targeted for disruption or destruction during a war on Earth. The ability to make dramatic maneuvers may increase their survivability. However, without the ability to refuel them or otherwise extend their lives (e.g., have power sources other than chemical propellant), the benefit of the maneuvers may be limited. Refueling and life extension are therefore of considerable strategic significance in a contested space environment.

4. R4: Repair

a. What is Repair?

A spacecraft being prepared for launch looks much different from when it is in orbit (Figure 2-1). A typical satellite has antennas and solar panels that are tightly folded and restrained, in order to fit within the fairing of the launch vehicle. Typical fairings today are 4 or 5 meters in diameter, whereas solar panels can extend 20 meters or more. Large communication satellites carry multiple large reflector dishes, which are also folded and restrained for launch. Shortly after launch, when the vehicle has reached a high altitude where air pressure is minimal, the fairing is discarded. Later, the satellite separates from the launch vehicle upper stage and begins deploying its solar panels and antennas. Occasionally, a solar panel or antenna will not deploy properly. This can greatly degrade the performance of the satellite. The value of correcting such a deployment anomaly can be hundreds of millions of dollars.



Source: https://jwst.nasa.gov/images/ariane4.jpgm, https://svs.gsfc.nasa.gov

Figure 2-1. James Web Space Telescope (LHS—in launch vehicle, RHS—after deployment)

Repair of such an anomaly would require a servicing vehicle equipped with robotic arms. Restoring the deployable component to its nominal in-orbit state could require simply applying a gentle force, vibrating the component, untangling it from insulation, or manipulating a restraining device. Typically, the repair activity would begin with inspection, followed by the servicing vehicle docking with the client, as this eliminates relative motion and enhances safety. Prior to docking, the repair servicer would image the client from several angles, providing information on the exact external configuration that would be used both to ensure safe docking and to plan the repair. Alternatively, another company could be contracted to perform the imaging in advance.

Assisting with deployments and repositioning insulation blankets is about the extent of repairs that could be accomplished on today's satellites. Almost all such repairs would occur at the beginning of the satellite's life, as that is when the key components are deployed.

If future spacecraft were designed with modular components that could be replaced on orbit (like the Hubble Space Telescope), module replacement could be another form of repair. Then repairs might occur later in the life of repairable satellites.

b. Why Conduct Repair?

Correcting spacecraft anomalies benefits not only the space insurance industry—the satellite owner/operator can also service the full range of customers on the ground, rather than having to wait years to build and launch a replacement satellite. Insurance does not cover the loss of business from such anomalies; lost business could amount to hundreds of millions of dollars over the life of the satellite. As an example, between 2004 and 2014, five commercial GEO communication satellites experienced deployment anomalies. The average insurance payout was $130 million. A more recent antenna deployment anomaly, onboard Viasat-2 in 2018, resulted in a $188 million payout. Had those satellites been repaired, those payouts may have been unnecessary.

While most repair concepts today are targeted at GEO clients, the technologies are in theory applicable to LEO as well. But as a practical matter, the diversity of LEO orbits means that a servicer today would be unable to reach multiple clients economically.

Correcting a deployment anomaly aboard the multi-billion dollar military satellites referenced above would be of great benefit to the taxpayers who would otherwise have to fund a replacement. Repair represents the timely restoration of the capability embodied in the satellite, rather than having to wait years for the replacement.

Given the monolithic[5] nature of today's military satellites, robotic capabilities are unlikely to provide any restoration of capability to satellites damaged during a conflict in space. Should future designs incorporate on-orbit replaceable modules, some restoration of capability (through replacement modules stored in space or launched post-conflict) might be achieved.

5. R5: Replace Parts

a. What is Replace Parts?

Many satellites, particularly the large GEO communication satellites, have mission lifetimes of over a decade. During that time, they may suffer from obsolescence, whether due to technology improvements or changes in subscriber needs. However, if their subsystems are still functioning nominally, they may still provide a valuable service by acting as hosts for new capabilities delivered and installed on orbit.

Current satellite designs are tightly integrated, lacking modularity or replaceable units. There has been no capability to perform on-orbit replacement; therefore, designs have not implemented such features. However, it is feasible to attach modules to the outside of spacecraft. Lacking connection points for power and communication, the modules must include their own power (solar panel) and communication means (radio). The modules could only be installed by a robotic servicing spacecraft, as dexterity is required to manipulate modules and actuate their attachment mechanisms in the precise location required.

For future spacecraft, modules could be delivered as hosted payloads or by dedicated launches. The ESPA ring, a secondary payload adapter often flown on GEO missions, is another avenue for delivery of modules for U.S. customers. Some launch providers, such as ArianeSpace, offer rides for secondary payloads for international customers.

If future spacecraft were designed in a modular fashion that allowed for replacement on orbit (like the Hubble Space Telescope), module replacement could enable upgrade of a satellite's primary functionality, rather than merely using it as a host for a separate capability. Commercial GEO satellite operators are particularly interested in the replacement of solar panels, which tend to experience reduction in power output with the passage of time.

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[5] As opposed to systems that are designed to be more modular, or systems composed of distributed satellites.

b. Why Conduct Replace Parts?

Commercial GEO satellites are typically built to a 15-year lifetime standard. Due to the advancement of technology, subscriber needs, preferences, and systems change much more quickly than a 15-year pace. For example, direct-to-home television broadcast from GEO was responsible for enormous growth in the GEO market beginning about a decade ago. However, today more subscribers are switching to video delivered over the internet, and the broadcast market is declining. Thus, the operators' returns from their large, expensive GEO satellites are declining. If an operator leased a satellite as a host for on-orbit-installed payloads, they would acquire an additional revenue stream. In the future, an appropriately built satellite could have its primary communications payload upgraded on orbit.

The on-orbit installation concept also offers entrepreneurial opportunities. GEO is the ideal location for generating persistent Earth sensing, relaying data, and other products. However, building and launching a GEO satellite is very expensive, typically hundreds of millions of dollars. In contrast, an individual payload could cost a small fraction of the cost of a fully integrated GEO satellite, and it could potentially be delivered to GEO for a small fraction of a typical launch contract via a ride share program. Arrangements for hosting payloads can be signed well in advance of the actual delivery and installation, and in principle represent steady, predictable revenue streams for the host platform and servicer.

Military satellites, like commercial ones, are typically built to a 10- to 15-year design standard. Strategic conditions can change dramatically over that period. New technologies can render the satellite obsolete. Intelligence can reveal weaknesses in a satellite's mission concept or in its vulnerability. On-orbit enhancement can allow military satellites to receive new sensors, processors, communication channels, or defensive capabilities in response to changing conditions. Because on-orbit attachable modules are less complex than a fully integrated satellite, they are less expensive to design and fabricate, and they can affordably be changed for newer versions more frequently than replacement of complete satellites. As in the commercial case, future military satellites could be designed in a modular fashion, increasing the advantages derived from on-orbit servicing.

6. R6: Recharge

a. What is Recharging?

Most satellites in Earth orbit today are electrically powered by photovoltaic (solar) cells. Solar cells degrade over time in space due to radiation damage, typically losing 1 to 4 percent of their power delivery capacity per year (Wertz 2010). Solar panels may also fail to deploy after launch, reducing a satellite's available power from the start of its mission. Without power, satellites cannot perform their primary function and will fail to generate revenue or returns on investment. In other cases, satellites may temporarily need more power than they can generate to respond to an off-nominal situation or operation. Recharging a satellite can provide the power necessary to conduct a satellite's nominal mission operations and extend the lifetime over which it can perform those operations.

Supplying more power to a satellite can be done two ways: through a direct connection with the spacecraft, or with remote power beaming. If a servicing spacecraft is already permanently docked with a client satellite, and the client satellite has the appropriate connection port, it can supply power with its own solar panels through an electrical connection, preferably the same port that would be used to transfer telemetry data to the servicing satellite if both satellites are designed to the same standards.

Power can also be supplied to a client satellite remotely through other methods. One method involves placing solar reflectors near the client satellite that divert sunlight directly to the client's solar panels. This method does not require the satellite to be designed with any special hardware and works with virtually all existing satellites.

If the power management system of a satellite can manage larger loads than the solar panels were designed to provide in direct sunlight, the solar panels could deliver even more power if sunlight is diverted from another direction. Solar panels deliver power that scales with sunlight intensity; if intensity is increased, power is increased. With a free-flying reflector nearby, the total solar irradiance on the solar panels would go up. Sunlight could also be directed at both sides of the solar panels potentially doubling the available power to the client satellite.

Other methods for remote power delivery involve power beaming using microwave wavelengths, either from a nearby servicing satellite or from a ground station. These satellites would require a power beaming receiver in order to harness this power. While space solar power is typically oriented toward beaming power from space to the ground, the same technologies can be used to beam power from the ground to satellites or between two satellites.

b. Why Conduct Recharging?

If a solar panel on a satellite is damaged and cannot be repaired, the satellite may not be able to operate. For example, Eutelsat's 5 West B satellite, launched in October 2019, could not deploy one of its solar arrays, leading to a 45 percent decrease in its power availability. Not only will this cause Eutelsat to lose between 5 to 10 million euros this fiscal year (ending June 30, 2020), it could cut the revenue it expects to generate over the course of its 15-year lifetime by as much as half and force Eutelsat to continue to operate the 17.5-year-old 5 West A satellite that 5 West B was intended to replace. Furthermore, the antenna pointing operations required to reoptimize the satellite to serve Eutelsat's customers could cost over 10 million euros (Henry 2020).

If a repair mission to a power-challenged satellite were deemed infeasible, a mission to provide more power to the satellite could help Eutelsat generate revenue closer to its original projections. An insurance agency could determine that a repair or dedicated recharge mission outweighs the cost of the claim, and any data gathered during the mission could be given to the manufacturer to prevent future solar panel deployment failures.

Furthermore, the ability to augment a satellite's maximum power on demand could have consequences for satellite design and operations. A satellite that can receive power even when it is eclipsed from the Sun by Earth can be smaller, and therefore stealthier and potentially less costly. Its solar panels can have a reduced radar cross section, and its entire power system can have less mass. It can conduct higher-power operations, even while orbiting over a nighttime location, with rapid response time and without fear of overspending its power budget. The ability to deliver power over long distances to satellites has myriad applications, especially in the warfighting domain, and could be disruptive to normal space operations. Limitations to this approach include the large area power collector the satellite would require, and the short period of time it spends over a power transmitting station on Earth.

B. On-Orbit Assembly

1. What is On-Orbit Assembly?

As introduced above, on-orbit assembly involves the on-orbit aggregation of components to build or add functionality to a spacecraft. Assembly is attractive for several potential applications. First, it enables the deployment of spacecraft that are too large to be launched as monolithic systems. The International Space Station (ISS) is an example of a crewed assembly mission of a large spacecraft. Its assembly required more than 40 space shuttle launches and more than 1,000 hours of extra vehicular assembly (Boyd et al. 2016). The next generation of very large space telescopes that could be too large, too heavy, or too delicate to launch in a single rocket fairing could also fall into this category. Second, assembly can allow spacecraft hardware to be upgraded with new, higher performance technology. Updating communications payloads (discussed above) is an example of such an assembly mission. Third, assembly of different payloads onto a persistent platform can provide flexibility and diversity for science missions. This category may include self-assembly of modular spacecraft that can reconstitute themselves for different purposes.

Successful development and demonstration of the technologies required for assembly may provide significant value for several potential applications. An important example of deploying space structures that are too large to be launched directly involves observation instrumentation. NASA's current large space telescope, the James Webb Space Telescope, has a primary mirror diameter of about 6.2 meters that only just fits into the largest available rocket launch fairing (5-meter diameter) when folded in thirds. For the next generation of missions, in order to study deep space objects at larger distance or higher resolution, larger telescope apertures will be required and folding will become impractical. For example, one study estimates that an aperture diameter greater than 16 meters is needed to be able to identify a sufficient number of exoplanets to have a high probability of detecting life on one of them (Beckwith 2008). Although launch rocket fairings of 7 and 8-meter diameter are planned, ultimately on-orbit assembly of large structures will become more practical (Boyd et al. 2016; Mukherjee 2019). Similar arguments can be made for the value provided by on-orbit assembly of large observation structures for viewing the Earth (for both science and national security missions) at all wavelengths. For example, a large structure on the order of 100 meters could be deployed as a high-resolution synthetic aperture radar.

A second category of application of on-orbit assembly involves the use of a persistent platform on which payloads can be attached and detached. An informative illustration of this concept is provided by the current so-called “A Train” Earth observation mission that is operated by NASA. The A-Train consists of a convoy of six spacecraft in LEO, each of which carries a unique science payload. These spacecraft pass over the same point in succession allowing a variety of different properties to be measured for a common region or event on the ground. A persistent platform could contain slots for six payloads. These could be launched two or three at a time and attached onto the platform. Compared to the coordinated deployment and operation of six different spacecraft, this approach would reduce costs significantly. Moreover, through modular design of the platform and payloads, it would be possible to replace the instrumentation periodically to allow measurement of other properties or to update measurement technology.

In the commercial sector, communications satellites provide a different illustration of the potential benefits of on-orbit assembly onto a persistent platform. As noted above, the typical operational lifetime of a communications satellite is about 15 years. While it makes sense to aim for many years of operation, given the significant upfront expenditure in launch costs, there are drawbacks to this length of operation. First, the communications hardware typically delivers bit rates that increase by about a factor of 10 every 7 years. Thus, over the lifetime of a communications satellite, the technology may advance by a factor of 100. The ability, through on-orbit assembly, to remove an outdated payload and to replace it with the latest system after several years could pay significant dividends for the communications satellite operator. In addition to updating technology, assembly could also allow the operator to respond to market changes by tailoring the payload in terms of the number of channels available and antenna design to meet evolving customer demand.

As illustrated by these two examples, the persistent platform concept clearly increases mission flexibility that would also find utility for missions of national security. For such missions, it could also provide a measure of resilience as sensors that become inoperable could be replaced. New sensors could also be deployed to meet the requirements of evolving threats.

Launch vehicles have become more capable over time, but still impose some limitations on their payloads. Launched mass is one limitation, but volume and geometric extension are also limited. The ability to assemble large, lightweight structures on orbit can overcome the geometric limitations. The solar arrays of the ISS, for example, span over 3,500 square meters, and would warp under Earth's gravity if fully assembled on the ground (Boyd et al. 2016).

The ISS is the only extant space object to-date that has been assembled in orbit by astronauts. Most assembly concepts being studied today envision the assembly being performed by robotic systems rather than humans. System concepts range from simple assembly tasks, such as installing antenna reflectors on the exterior of a communication satellite, to constructing a large space telescope from numerous modular components.

Today's satellites are completely monolithic, fully assembled prior to launch. While they may have some deployments post-launch, they do not require assembly. Future spacecraft could be designed in a partly or completely modular fashion that allows for assembly at an orbiting "satellite factory." If the factory is in LEO, some modules might be delivered by any of the low-cost, low-payload launch vehicles beginning to appear on the market. The ESPA ring, a secondary payload adapter often flown on GEO missions, is another avenue for delivery of modules.

2. Why Assemble in Space?

A major economic driver in today's space industry is its support of global communications. The internet is growing by 26 percent a year, and interconnection between businesses is growing at 48 percent a year (Coughlin 2018; NCTA 2019; Price 2019; Jarvis et al. 2019). Experts predict that every type of communication system—space, fiber optic cables, microwave, or optical communication—will have to develop new technologies to support this demand. In space, bandwidth capacity can be increased by deploying larger antennas and more powerful platforms—and space robotics will be called upon to construct these systems in orbit, which has advantages compared to traditional satellite designs.

A large reflector for a communications satellite enables more customers to be served. Low frequency systems can deploy large reflectors made of wire mesh that unfold like an umbrella on orbit. However, satellite communications are moving to higher frequencies, where wire mesh antennas lack the precision shapes required. High frequency antennas require precision surfaces. In the future, large antennas could be launched as precisely machined subpanels and assembled on orbit by robotic systems.

Similarly, the power available to a satellite from its solar arrays also influences how many customers can be served. Recent advances in solar array design have increased the maximum power available. Even more power could be made available by installing additional solar arrays on a satellite or platform after it reaches orbit.

Modular satellites have several potential economic advantages compared to today's monolithic designs. The more complex a launched object is, the more challenging to design it to survive launch conditions. By taking advantage of on-orbit assembly, the requirements for certain tests of the integrated satellite, particularly vibration, are eliminated; only the individual modules need to be tested. Significant cost and mass savings can be achieved in this manner, as much of the structure for launch survival is now unnecessary; stresses experienced by a satellite on orbit are very small. Also, by accessing smaller, cheaper launch vehicles, total launch cost may also be reduced.

Large reflectors for radio signals are important for communications, but also for missions such as location of adversary transmitters on Earth. Reconstitution of space assets following a conflict might occur more quickly if satellites were modular and small launch vehicles could be used.

C. On-Orbit Manufacturing

1. What is On-Orbit Manufacturing?

As introduced above, on-orbit manufacturing involves the on-orbit transformation of raw materials into usable spacecraft components. On-orbit manufacturing primarily consists of sending raw materials or feedstock into orbit (though the resources of space can also be used as feedstock and transformed in more advanced cases) and using machinery to turn the feedstock into the desired components. Compared to on-orbit servicing and assembly, on-orbit manufacturing is in its technological infancy (Boyd et al. 2016).

The simplest on-orbit manufacturing technique is additive manufacturing of single materials. For example, the first 3D printers in space used plastic feedstock to manufacture simple structures and tools. More advanced 3D printers will use multiple materials, including metals, ceramics, and semiconductors. Subtractive manufacturing techniques, such as milling and grinding, also an element of on-orbit manufacturing, are more challenging in space because of heat transfer and debris capture issues.

While most of today's applications involve adopting terrestrial manufacturing technologies for use in space, future manufacturing processes can take advantage of the microgravity and vacuum environments of space to create products that are impossible to create on Earth, such as exotic crystal structures and delicate sensors. STPI does not consider manufacturing products in space to send back to Earth within the scope of this report, but the basic research to expand on techniques will be relevant for all on-orbit manufacturing.[6]

Feedstock sent from Earth is not the only source of material that can be transformed through on-orbit manufacturing; the resources in space can also be captured and transformed into usable products as well. The vast majority of research in this area surrounds *in-situ resource utilization* (ISRU), which STPI considers as using the *natural* resources of space, such as materials from the Moon, Mars, and asteroids; *recycling* is when materials from *manufactured* objects, such as discarded rocket bodies or old satellites, are transformed. ISRU requires many materials processing and separation technologies to break natural regolith down into its constituent components, whereas recycling requires more cutting and manipulation but fewer materials purification techniques since the recycled material is likely pure enough in its current form to not require chemical transformation before it can be physically be transformed for other purposes.

On-orbit manufacturing on robotic (uncrewed) platforms will also rely heavily on many of the same technologies and capabilities that are required for on-orbit assembly. After a component is manufactured, it will require manipulation, assembly, joining, and positioning to enable its functionality on the spacecraft. Most terrestrial joining techniques, such as welding, are feasible in space. The ability to evaluate the accuracy of manufactured structures and conduct other verification and validation activities will become increasingly important as the complexity of manufactured items expands.

2. Why Manufacture in Space?

On-orbit manufacturing presents many potential advantages. These advantages include overcoming traditional launch constraints, creating flexibility and other advantageous lifecycle properties in systems, and enabling long-term sustainable human exploration (Boyd et al. 2016).

To an even greater extent than on-orbit assembly, manufacturing components in space would relieve many of the constraints imposed by launch vehicles. On-orbit manufacturing would eliminate the need to make individual spacecraft components ruggedized in order to survive the harsh vibrational and thermal environment of launch, as long as the feedstock for the components that would be manufactured can survive. Feedstocks, whether spools, powders, or liquids, can easily be packaged to withstand launch.

Packing raw feedstocks into a fairing for on-orbit manufacturing is also geometrically efficient and could be accomplished with almost perfect volumetric efficiency; in contrast, fully assembled, geometrically complex spacecraft assembled on the ground cannot be as

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[6] STPI has evaluated on-orbit manufacturing for use on Earth in other reports such as Crane et al. 2017.

densely packed and requires a larger fairing, leading to expensive aerodynamic inefficiencies during launch. Manufacturing in space not only reduces geometric constraints and eliminates even more of the structural mass required for a satellite system than on-orbit assembly, it enables technologies, such as gossamer structures, that could not be conceived for use within the current launch paradigm.

Manufacturing components and tools as needed through the execution of a mission could enhance resilience and flexibility, both in satellite missions but especially in human spaceflight missions. The 3D printers deployed to the ISS represent a first step in this direction. For long-duration space exploration missions, the ability to manufacture components on an as-needed basis has the potential to significantly reduce the inventory of pre-manufactured items that must be launched and transported throughout the mission. For example, instead of requiring an extensive tool set for all possible scenarios, tools are only printed as specific issues arise through the course of the mission.

The use of ISRU to generate input material for on-orbit manufacturing is most relevant for enabling long-term, sustainable deep space exploration, although some experts argue that space-based solar power for Earth is also a compelling application. NASA’s concept for a permanent gateway near the Earth-Moon Lagrangian point would be greatly facilitated by the ability to manufacture structures for exploration vehicles from lunar surface materials and producing consumables such as drinkable water, breathable oxygen, and rocket propellant.

As noted above, manufacturing components in space will make it possible to increase the complexity of spacecraft while reducing costs of design and making components more rugged. Many nations are beginning efforts to exploit resources found on the Moon. Some lunar materials may be suitable for on-orbit manufacturing. Primary among these are metals extracted from lunar ores, sintered lunar regolith, and silicates that can be transformed into solar panels to generate power (Colvin et al. 2020).

D. Technologies Required to Develop OSAM Capabilities

The areas discussed above are capabilities. These capabilities are enabled by a series of underlying technologies working together. For example, in the use case of R2: Relocation to deorbit a LEO satellite, the servicing spacecraft has to find the satellite, make a close approach without collision, dock with or connect to the satellite, and finally push it into a lower orbit. Each of the steps is enabled by a specific set of technologies.

1. Technologies Required for OSAM

STPI identified 23 technology areas that are critical, desired, or enabling for various OSAM activities.

- Rough-Control Propulsion: The ability to maneuver in space. Required for all RPO.
- Fine-Control Propulsion: The ability to maneuver in space with fine control. Required for close RPO, rendezvous, and docking.
- Basic Guidance, Navigation, and Control: The ability to navigate to another RSO.
- Advanced Guidance, Navigation, and Control: The ability to navigate and match velocity with another RSO, including ones that are tumbling.
- Automation (Basic): The ability to do basic functions without humans in the loop.
- Automation (Advanced): The ability to perform complex operations, such as an entire servicing mission, without humans in the loop.
- Artificial Intelligence (AI)/Machine Learning: The ability to recognize patterns and make decisions based on sensor inputs or other data.
- Fiducials: Markings on a spacecraft that make it easier to judge relative position and velocity. Highly desired but not required for docking and other activities.
- Computer Vision: The ability to judge distance, velocity, and spatial awareness. Fiducials make this easier.
- Basic Robotic Arms: Manipulators that can perform basic mobility and move with sub-centimeter precision.
- Advanced Robotic Arms: Manipulators that can operate with extreme positional accuracy to perform functions such as repair circuit boards and align and manufacture optical components at near-micron precision or better.
- Intra-Spacecraft Mobility: The ability of a robotic arm system to move around a spacecraft to reach other parts.
- Standard Interfaces: When two satellites are connected physically after docking, they must make other connections to transfer data, power, and fuel for more advanced servicing missions. Standard interfaces make this possible. STPI includes fuel transfer technologies within this technology area, even though technologies for fluid transfer in microgravity vary greatly. Fuel transfer typically requires advanced thermal management, sloshing monitoring, pressurization systems, and many others depending on the fuel type. Standard interfaces for transferring power and data are significantly simpler, but if the client satellite is not outfitted with these interfaces, the servicing activities associated with interfaces will also be impossible.

- Modular Payloads: Payloads that can be more easily swapped out, or more easily manipulated by robotic components, with interfaces that make operating on them simpler, are essential for R5: Replace Parts and operation of persistent platforms. Modularity also eases challenges in R4: Repair, and makes integration and testing on the ground easier.
- Cutting Tools: The ability to cut materials, such as insulation blanketing, wires, or thin metals. Useful for accessing ports buried under insulating material, separating broken materials, and other dual-use applications.
- Space Welding: The ability to join materials in space that were not designed to be assembled together, or the ability to cut thicker material like metal.
- Verification and Validation: The ability to determine if a part assembled or manufactured on orbit meets the requirements and needs of the customer. AI and machine learning are important prerequisites.
- Additive Manufacturing: The ability to transform a single material into simple shapes via 3D printing techniques.
- Multi-Material Manufacturing: The ability to transform multiple materials into complex shapes, such as circuit boards. This is not limited to 3D printing and can include chemical vapor deposition and other processes that take advantage of the vacuum environment of space.
- Materials Separation: The ability to separate raw materials (e.g., lunar regolith) or complex systems (e.g., circuit boards) into chemical components that can be used for other manufacturing purposes. This includes volatile separation and low-temperature melting.
- Industrial Processing: The ability to separate and transform materials into elemental components that can be used for other manufacturing purposes. This includes metal separation and purification and high-temperature melting.
- Space Nuclear Power: The ability to generate high power (> 1 MW) using nuclear fission reactors in space.
- Wireless Power Transfer: The ability to transfer power without a physical connection.

Many technologies within OSAM share similarities depending on the specific application, but some technologies required for multiple applications could have very different technical requirements.

With the exception of some special applications in R1: Remote Survey and R6: Remote Recharge, all satellites engaged in satellite servicing must be able to perform RPO. The act of matching speed and position with a spacecraft in orbit requires a number of sensors, algorithms, and guidance, navigation, and control (GNC) technologies. An independent satellite conducting R1: Remote Survey in the same orbit as the satellite it is surveying requires less advanced RPO given the satellites do not have to come close to one another. For any other satellite servicing application, docking with a satellite is required.

One challenge with satellite servicing is that most satellites on orbit today have not been designed to be serviced; therefore, there is a higher difficulty barrier present today to perform satellite servicing than there will be in future if satellites are designed to be serviced.

Docking with another satellite, especially one not designed to be docked with, requires several technologies. Robotic manipulator arms and computer vision technologies must be more advanced for non-cooperative satellites than for satellites with appropriate fiducials, docking mechanisms, and servicing ports. Tumbling satellites and debris are even more difficult to dock with and require advanced maneuvering of the servicing satellite while also manipulating the client satellite.

AI is needed to reduce the risk of an accident in the event of a loss of communications. Satellite servicing operations will likely be conducted without humans in the loop.

2. Relevant Technologies for Each OSAM Activity

Table 2-1 provides our best assessment of whether each technology area is critical (C), desirable (D), or enhancing (E) for specific OSAM capabilities. “Critical” technologies are required to perform even the most basic versions of the activity listed in each column. “Desired” technologies are not required for the activity but make the operation easier or could provide a capability that makes a more advanced version of that activity possible (e.g., intra-spacecraft mobility is not required to perform R4: Repair on a typical satellite, but could be helpful for any repair mission and is likely required to conduct repairs on a large persistent platform). “Enhancing” technologies can improve the efficacy of an activity or provide new avenues to conduct the activity that make it more competitive than it would be without the enhancing technology (e.g., nuclear thermal propulsion would make a more efficient satellite tug that could engage in R2: Relocation with better results).

Table 2-1. Relevant Technologies to Develop OSAM Capabilities

	R1: Remote Inspection	R1: Close Inspection	R2: Orbit Maintenance	R2: Orbit Transfer	R2: Deorbit	R3: Refuel	R4: Repair	R5: Replace Parts	R6: Ground Beaming	R6: Solar Reflection	R6: Direct Power	A (Basic)	A (Precision)	A (Platforms)	M (Basic)	M (Advanced)	M (ISRU)	M (Recycling)
Rough-Control Propulsion	C	C	C	C	C	C	C	C		C	C	D	D	C	D	D	D	C
Fine-Control Propulsion	D	C	C	C	C	C	C	C		D	C			C				
Basic GNC	C	C	C	C	C	C	C	C	D	C	C	D	D	C	D	D	D	C
Precision GNC	D	C	C	C	C	C	C	C		D	C	D	D	C	D	D	D	C
Automation	D	C	C	C	C	C	C	C	D	C	C	D	C	C	D	C	D	C
AI/Machine Learning												D	C	C	D	D	D	C
Fiducials		D	D	D	D	D	D	D			D		D	D		D		D
Computer Vision	D	C	C	C	C	C	C	C		D	C	D	C	C	D	D	D	C
Basic Robotic Arms		C	C	C	C	C	C	C			C	C	C	C	D	D	D	C
Precision Manipulators			D	D	D	D	D	D			D	D	C	D	D	C		D
Intra-Spacecraft Mobility						D	D	D			D	D	D	C				D
Standardized Interfaces		D	D	D	D	C	D	C			C	D	D	C	D	D		
Modular Payloads						D	D	C			C	D	D	C	D	D	D	D
Cutting Tools						D	C							D	D	D	C	C
Space Welding														D	D	C		C
Verification & Validation							D	D				D	C	D	D	C	C	C
Additive Manufacturing												D	D	D	C	C		
Multi-Material Add. Man.														D	D	C		
Materials Separation																D	C	E
Industrial Processing																D	C	C
Wireless Power Transfer									C	D				E		E	E	E
Space Nuclear Power				E	E									E		E	E	E

Note: Cells shaded in green (labeled C) are critical to achieve a particular OSAM capability; cells shaded yellow (labeled D) are desirable; and cells shaded blue (labeled E) were designated as enhancing.

As might be expected, technologies such as propulsion or guidance and navigation are important for all OSAM capabilities, and others such as wireless power transfer apply only to one or two areas. RPO are basic prerequisites for all servicing activities as well as for most major assembly and manufacturing activities. Thus, the technologies required for RPO form the core for most of OSAM. Figure 2-2 shows our best assessment of the prerequisite technologies for satellite servicing, and Figure 2-3 shows the prerequisite technologies for assembly and manufacturing; solid lines show required technologies, while dotted lines show desired technologies that can ease other burdens in the activity.

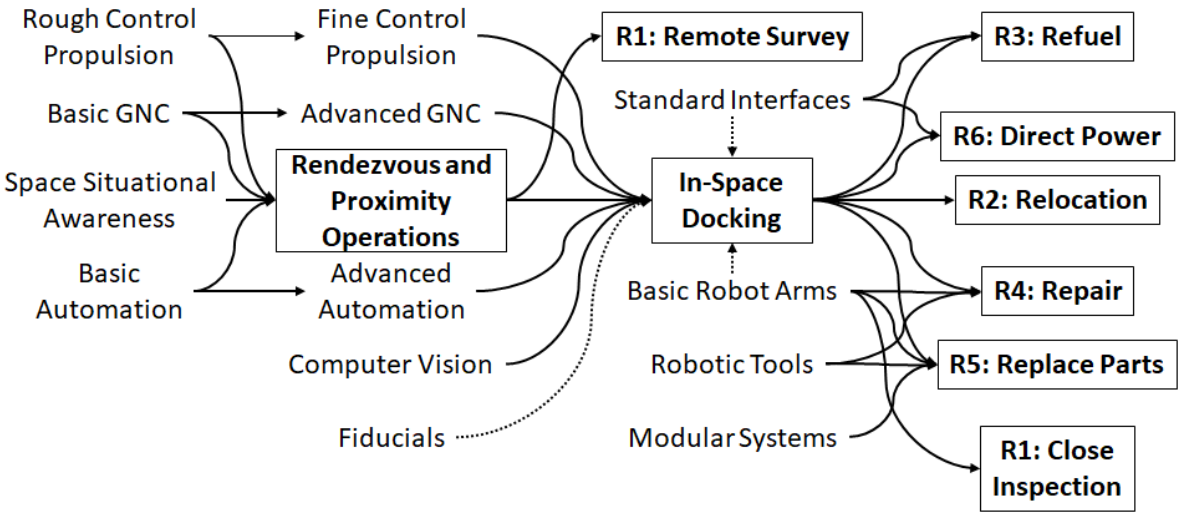


Figure 2-2. Technologies Required or Desired for On-Orbit Servicing

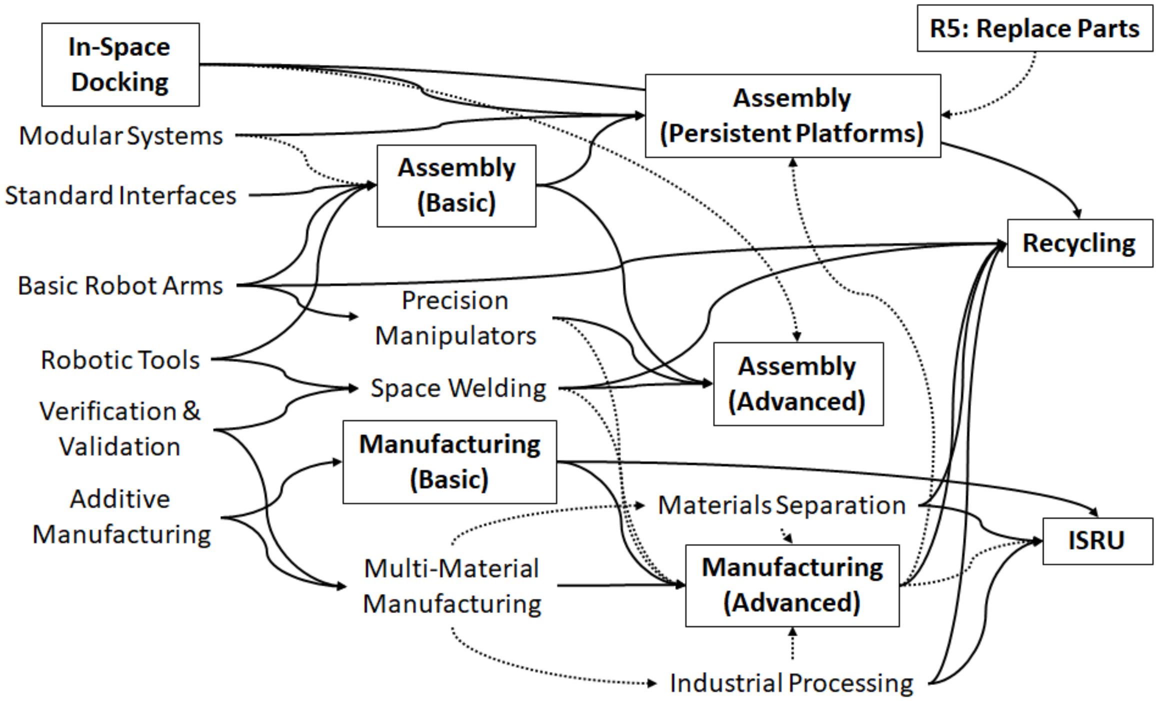


Figure 2-3. Technologies Required or Desired for On-Orbit Assembly and Manufacturing

E. Impact of OSAM Capabilities

The possible advantages of OSAM are multiplied when synergies between the use cases above are considered. OSAM capabilities have the potential to transform the entire space domain.

If manufacturing standards to design for serviceability of satellites and modularity of payloads become the norm for new space systems, the potential customer base for servicing missions could grow. Such modularity and standards may help create and grow an ecosystem of users and suppliers with hardware that could look vastly different from the current generation of custom-designed satellites, each with their own bus and subsystems. Payloads may have lower lifecycle costs when operated from persistent platforms with other payloads that can be switched out or upgraded on a predetermined schedule. Payload switching and upgrading would also provide flexibility to allow space companies to more quickly react to market demand or prevent oversaturation and limit losses if a market does not materialize.

If refueling options grow, the lifecycle cost for maneuvering satellites could go down and eliminate the need to end a satellite's mission when all of its propellant is expended. This would allow some satellites, especially exquisite military satellites, to perform maneuvers much more often than they do now, therefore enabling satellites to be more responsive to their payloads' needs and better maximize the returns on investment. Routine maneuvers for all satellites in LEO may be necessary if the risk of space debris in LEO continues to grow; if refueling services are available, it is more likely that actors would behave responsibly since maneuvering would be less costly over the long term. Better space situational awareness (SSA) and space traffic management (STM) could also help actors make better decisions to reduce risk of orbital collisions.

If refueling missions become common enough, operation of in-space infrastructure like fuel depots could be sustainable. Depots can be attached to other facilities, such as for research or human habitation, allowing revenue streams to help sustain a collaborative enterprise. The availability of depots would change the culture of design for many missions, both for constellations of large satellites and human spaceflight missions. As refueling missions become more commonplace, refueling operations can help make high delta-V missions more feasible, such as human spaceflight missions beyond LEO and planetary science missions to the outer planets.

Relocation today is being implemented in the GEO arc with relatively small orbit changes—between GEO slots, or from GEO to the graveyard. However, a reusable relocation servicer that transports payloads from LEO to GEO could have economic benefits. Today, a single-use second stage pushes payloads out to GEO. A reusable space tug for LEO-to-GEO moves would enable smaller launch vehicles to be used, lifting their payloads only to GEO. This is the same philosophy that drives launch companies such as

SpaceX to reuse their first stages. Of course, the long-distance reusable space tug would have to be refuelable.

Maturation of assembly and manufacturing technologies could further change how large space systems are designed and integrated into launch vehicles. On modern communications satellites, large booms that hold antennas must be strong enough to survive launch and deploy on orbit. If a robotic system is launched along with a satellite to assemble it on orbit, the satellite would not need those booms, and other structural mass could be saved. Assembly on orbit would also eliminate a number of volume constraints, as the volume inside the launch fairing can be better utilized. The satellite could also be reconfigured on-demand to alter the satellite to quickly respond to market needs, a massive shift in today's paradigm. If assembly can be combined with RPO, volume constraints on payloads can virtually be eliminated since multiple launches could be used to construct a satellite or space system.

Missions that require multiple launches must be designed differently from single-launch missions. Having multiple launches means RPO is needed for each payload; in order to avoid equipping each payload with RPO capabilities, space tugs can be used, providing a reusable RPO system. Launch vehicle failure can terminate a single-launch mission or extend the schedule dramatically; multiple smaller launches may be cheaper than a single large launch in a space economy with competition and availability of smaller vehicles, and the overall mission risk involved in a single launch is lower, especially if that part of the payload is easier to replace than the entire payload. For missions with international collaboration, each collaborator can be responsible for their own launch and join the rest on orbit. Growth of OSAM capabilities could also eliminate the need for super-heavy lift launch vehicles altogether.

Assembly and manufacturing of larger space systems on orbit enables those spacecraft to be launched with multiple launches, and the sum of the costs to launch the same mass could be lower because of mass production (and reusability) of those launch vehicles. Large pieces of systems that can be modularly connected or the raw material to construct those pieces can be launched into space to augment existing facilities. Large masses of materials or propellant would be launched on large launch vehicles to minimize cost-per-kilogram, while systems that require more responsiveness would be launched on smaller vehicles that have a higher cost-per-kilogram launch cost but a lower total launch cost.

The ability to manufacture basic satellites in space on-demand and transport them to their desired orbits could allow for fast response to global events, such as natural disasters and war. Advanced manufacturing that includes circuit boards and software-defined radio payloads would change many operations and tactics and skirt launch licensing and reporting norms. However, such a facility with the ability to build and launch satellites on-demand from orbit would be a major target in any space confrontation; it would also compete with similar facilities on the ground that could launch using small rockets on-demand.

If an entity gains considerable experience with RPO on uncontrolled space objects like space debris, maneuvers in Earth orbit become cheaper due to high-ISP technologies like nuclear thermal propulsion, and the technologies to recycle material on orbit become available, many things can change. It would be economical to retrieve space debris like rocket bodies and transform the mass into new space systems. Dead satellites would not have to go to a graveyard orbit, but could instead be broken down and turned into new satellite systems.

More activities involving in-space manufacturing could lead to more research in industrial manufacturing, which could lead to new products that can only be produced in space. The industry has only begun to explore the possibilities of materials and products that require microgravity and vacuum to be produced. Exotic possibilities like high-quality fiber optic cable, solid synthetic diamond windows for aircraft, and human organs grown with customer DNA are, according to STPI's interviews with experts, within the 15-year horizon this report examines.

The United States plans to return to the Moon in this decade. This plan may include the assembly of an outpost in cislunar space, which could also serve as a logistics hub for vehicles traveling between the Earth and the Moon. Having this outpost serve as a fuel depot would increase the resilience of missions to and from the surface by on-demand backup options without the need to wait for a launch from Earth.

ISRU technologies could extract water from the lunar surface and convert it into usable propellant, reducing the cost of the logistics chain and providing fuel at the location where it would be the most expensive to deliver from Earth. This would greatly transform the nature, pace, and mission operations of human exploration campaigns and allow more surface area of the Moon to be explored in short time.

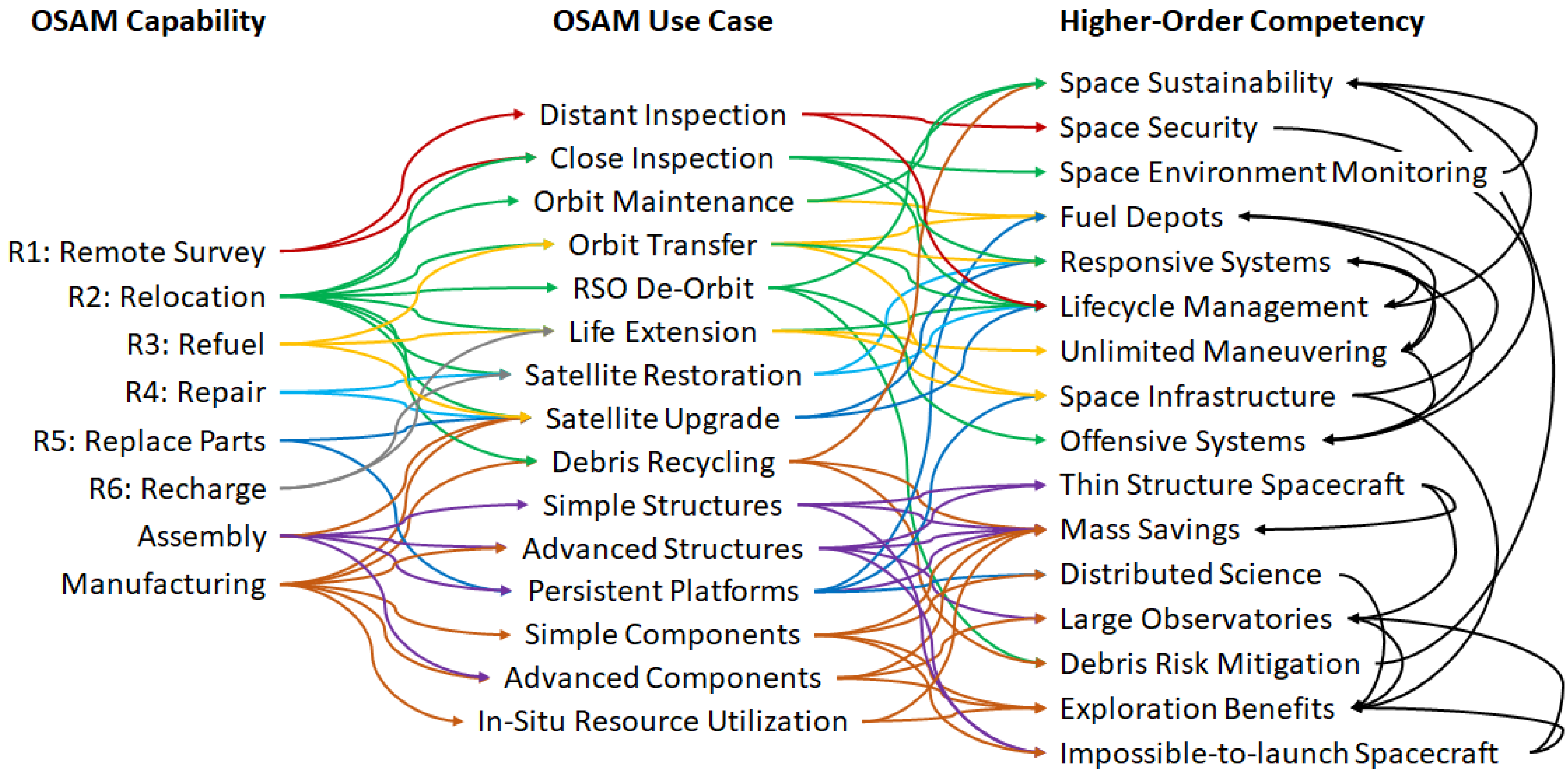
Not all spacecraft use the same propellant on orbit. Propellant depots could have influence on design choices for rocket engines in space. While some propellants are more easily stored on orbit, the transition to a water-based propellant economy due to lunar ISRU would influence the design of future spacecraft. The decisions affecting the market for propellant would likely be made long before propellant derived from the lunar surface is available.

The technologies that are required for or can greatly increase the utility of OSAM, such as robotic arms, nuclear power systems, and AI, can also benefit human and robotic space exploration missions. Nuclear thermal propulsion can propel planetary science satellites to outer planets faster and enable cheaper missions to visit more planetary moons or asteroids with a single load of fuel. Surface nuclear power can provide energy for larger-scale ISRU to make habitats more survivable, resilient, and sustainable. Space robotics and

AI can work with humans to explore planetary surfaces, especially when augmented with satellite data from above. A broad technology development portfolio that incorporates not only the development but also the required use of OSAM capabilities would have broader benefits to other space missions.

The technologies of OSAM could be used for destructive purposes as well. The same technologies required to cut multi-layer insulation to reach a fuel valve in a refueling mission could also be used to cut electrical cables of another satellite. The same instruments used to weld metals to form human habitats could be modified to cut antennas off satellites. Power beaming technology could be used to power one satellite during eclipse one minute and overload the power management systems of another the next minute. Drills and materials processing machinery used to pulverize extraterrestrial regolith could also be used to grind a working satellite into scrap. As the OSAM field grows internationally, the United States must be alert for signs of such adverse developments; some are already alleged to be in progress (Chen 2019).

Figure 2-4 shows the mapping of OSAM capabilities to OSAM use cases that STPI has identified to a selection of higher-order competencies that OSAM can enable.



Note: The color between the second and third column represents the most dominant OSAM capability that enables the higher-order competency.

Figure 2-4. Use Cases and Higher-Order Competencies Enabled by OSAM Capabilities

3. The Presumed Value Proposition of OSAM

In Chapter 2, we discussed the potential advantages and applications of OSAM. It is important to differentiate between what is technologically *possible* versus what is economically *feasible* or otherwise advantageous for a mission. In this chapter, we examine several OSAM use case scenarios and why, despite clear advantages for OSAM use, it may be difficult to adopt OSAM capabilities for missions, both government and private. The scenarios presented in the first three sections are hypothetical and use our best guesses for numerical assumptions.

A. Servicing

1. R1: Remote Survey

a. Scenario 1: Long-Distance Survey

The fee for a remote imaging mission could range from $0.5 to $3 million, depending on the required timeliness, number of images required, and other factors. Identification of a particular failure (e.g., partial antenna deployment) could assist the insurance underwriter in partial recovery of an insurance claim. If 10 percent of a claim were recovered ($13 to $19 million), the net benefit to the underwriter would far exceed the cost of the imaging mission.

b. Scenario 2: Ultra-Close Inspection

Ultra-close inspection is a higher-risk operation than remote imaging. Docking is a prerequisite, which involves extensive planning and rehearsal. Remote imaging is also a prerequisite; since presumably the client satellite has experienced a deployment anomaly, determination of its external configuration is required for safe approach and docking. The fee for an ultra-close inspection mission could range from $5 to $15 million. Possibly a higher percentage of an insurance claim could be recovered by the underwriter, given the higher level of detail produced. However, ultra-close inspection might also lead to the ability to correct a deployment anomaly. If so, the insurance claim could be completely avoided; also, full service could be restored at once, rather than awaiting the manufacture and launch of a replacement spacecraft.

2. R2: Relocate

a. Scenario 1: Change of a GEO Slot

To move around the GEO arc, a satellite must change its relative velocity. Consuming 2 months' worth of station-keeping propellant will provide a relative motion of about 1 degree per day, or 90 degrees in 3 months. The cost to the operator would be $7 million for the lost operating time due to fuel use, and $10 million for the lost operating time while drifting (assuming $40 million in annual revenue). If a servicer were to charge $8 million and effect the slot change in 1 month, the net benefit to the client operator would be about $6 million ($7 million in operating time saved from fuel conservation and $7 million from the speedier slot change, minus the $8 million servicing fee.)

It is unclear whether the $8 million fee would provide sufficient revenue to the servicer. If a $200 million servicer can execute 50 relocation missions, $8 million per mission represents a 50 percent return. The key to profitability would be designing the servicer to be able to carry enough propellant for 50 missions. Refueling the servicer every 25 missions at a cost of $100 million would make this unprofitable to the servicer. As launch costs decrease, refueling the servicer will represent less of a penalty.

b. Scenario 2: Deorbit/Disposal

A GEO satellite requires about 6 months' worth of station-keeping propellant for its final disposal maneuver. Due to conservatism in fuel-remaining calculations, perhaps another 6 months to 1 year of fuel will remain post-disposal. Together this fuel represents a loss of potential revenue of $40 to $60 million, assuming the satellite was still economically productive. A disposal contract with the servicer for $8 to $12 million (20 percent of the restored revenue) would also ensure that the satellite was not stranded in its GEO slot, incurring the risk of loss of the slot. It is difficult to estimate the value to the GEO operator of deferred capital expenditure.

c. Scenario 3: Space Debris Removal

The potential of damage from debris is much higher in LEO than in GEO, due to the much higher concentration of objects and the higher crossing velocities. Assessing the economic penalty due to space debris is challenging, much like assessing the penalty of climate change. An example will be used to provide a rough understanding of the cost and benefit of removing a single debris object.

There are numerous rocket bodies left in orbit by the former Soviet Union, each weighing many tons and in orbits that intersect. The collision of any two of these objects could generate tens of thousands of new debris objects. For the sake of example, assume that a collision was projected to occur such that it threatened the Iridium constellation (annual revenues of $400 million, or $6 billion total over the constellation's expected lifetime.) A propulsive vehicle with sufficient thrust and control to deorbit a large rocket body might cost $100 million—launching it into the correct orbit another $60 million. The benefit of executing this mission is in the billions of dollars, not to mention that other LEO satellites would also be threatened by the large debris event. The cost might be shared between Iridium and its insurers, with the potential of partial cost recovery from Russia.

However, determining collision probability is difficult, and without clear and present danger, most operators, private or government, would be hesitant to act. If the price of deorbiting a satellite in LEO is in the single digit or tens of millions of dollars, it is unlikely that operators would be motivated to pay to deorbit the satellite (unless they see a business case or are required to do so). This misalignment was evident when LEO operator Iridium floated a price of $10,000 they would be willing to pay to deorbit a satellite. This value is orders of magnitude lower than the $130 million that ESA contracted ClearSpace for removing a rocket body, and likely one to two orders of magnitude lower than the prices being offered by startup companies such as Astroscale or Effective Space (Henry 2019).

3. R3: Refuel

a. Scenario 1: Refueling

For a 4,000-kilogram GEO satellite, approximately 1.5 percent of its mass per year in propellant is required for station-keeping using chemical propulsion (bipropellant). Only about 0.3 percent of its mass in propellant is required per year if the station-keeping uses electric propulsion (xenon propellant). The cost of the propellant is about $20,000 per kilogram if efficiently delivered to GEO. A 3-year life extension could be worth $120 million to the operator. The cost to the servicer is $4 million for bi-propellant or $800,000 for xenon. The servicer must also account for the cost of the servicing vehicle itself: a refueler will probably be no less than $400 million plus a $100 million launch cost. The servicer could be expected to perform 50 missions over its life. So, with a fee of $24 million (20 percent of perceived client value) minus fuel cost and amortized servicer cost, the net profit to the servicer could be $12 to $15 million per refuel.

b. Scenario 2: Life Extension by Attachment

A life extension vehicle should cost much less than a refueling vehicle, because the robotics are either simpler or unnecessary. A 15-year life servicer could cost perhaps as little as $100 million, and share a ride to GEO for $50 million. However, the vehicle must stay continuously attached to its client. Thus, a 3-year life extension mission represents a cost of $30 million to the servicer for the amortized vehicle cost. To achieve a $12 million profit from such a mission, the servicer would have to demand a fee of $42 million.

4. R4: Repair

a. Scenario 1: Commercial GEO Satellite

The recent deployment anomaly on Viasat-2 resulted in a $188 million insurance claim being paid. Had a robotic servicer been available, the servicer's fee might have been paid jointly by the satellite insurer and its owner. As an example, two payments could add up to a fee of $137 million: $37M from the underwriters, representing 20 percent of the avoided insurance claim; and $100 million from the owner, representing 20 percent of lost revenues for the first 5 years of operation (assuming the anomaly caused a 5 percent reduction of Viasat's $2 billion in annual revenue).

b. Scenario 2: Military GEO Satellite Repair

Suppose a soon-to-be-launched advanced extremely high frequency (AEHF) satellite costing $1.4 billion were to experience a deployment anomaly that caused a 50 percent reduction in capability. A servicer proposing a $140 million fixed fee to restore full capability should receive a favorable determination from the government. Benefits to the government include avoiding delay in establishing the complete AEHF constellation's functionality, and avoiding the cost of a replacement spacecraft.

5. R5: Replace Parts

a. Scenario 1: On-Orbit Module Attachment

A payload for obtaining imagery data of the Earth could cost from $5 million to $50 million depending on its capabilities. Markets for such imagery include agriculture, meteorology, land use assessment, and environmental monitoring. A reasonable cost for a 100 kg GEO-qualified optical payload would be $20 million. The payload could be delivered to GEO as a secondary payload on a host GEO satellite, with the host charging a delivery fee of $10 million. Similarly, the fee for installation by a servicer could be $10 million. Assuming annual sales of imagery of $20 million over a 5-year payload life, the total return to the entrepreneur would be $50 million.

b. Scenario 2: Communications Payload Upgrade

A high-power GEO communications payload (not the entire satellite) may have a mass of 1,500 kg and cost $150 million, generating $40 million per year revenue for the operator. Since there are no launch vehicles directly addressing this class of payload, delivery to GEO would require a dual manifest, direct inject launch (for a Falcon Heavy, half the launch cost would be $55 million). The servicer operator could charge $20 million for capture of the payload, delivery and installation on a multi-payload GEO platform, and disposal of the old payload being replaced. The total cost of $225 million is only about half of the cost of putting the same payload in GEO on its own spacecraft bus, for the same capability. The multi-payload platform provides power, station-keeping and attitude control, for an annual $5 million hosting fee. The payload operator has saved $200 million in capital costs but annual revenue is reduced from $40 million to $35 million.

6. R6: Recharge

a. Scenario 1: Remote Recharge

An economic case for a satellite that requires ground-based power beaming on a regular basis has not been made, and the complexity of the tradeoffs and uncertainty of costs is beyond the scope of this study. Instead, we examine a special case of existing satellites that could, in principle, benefit from temporary recharging services.

In January 2020, a DirecTV satellite experienced a battery failure on orbit that could cause it to explode (Henry 2020b). Because of this failure mode, and because the GEO satellite would have passed through Earth’s shadow in February, the satellite had to be moved to a graveyard orbit, and DirecTV’s customers were rerouted to other satellites. If it were possible to temporarily beam power to the satellite to avoid the use of its batteries, it could have continued providing service until it ran out of fuel in 2025. Another 5 years of operation could have been gained if the satellite had the ability to receive power from the ground or if more sunlight could have been redirected from an alternate angle.

b. Scenario 2: Contact Recharge

If a GEO satellite’s solar panels fail to deploy on orbit, it could mean total failure or that the satellite will only generate a fraction of its expected revenues. In the case of Eutelsat 5 West B, it could reduce the satellite’s revenue by 5–10 million Euros per year and require additional operations cost to deal with antenna pointing issues over the course of its lifetime (Henry 2020a).

Eutelsat 5 West B was designed to operate for 15 years, meaning it could lose over 150 million Euros over the course of its lifetime. A servicing satellite would likely cost less than the 15-year net present value of the lost revenue. If a servicing satellite was unable to shake a solar panel that has been stuck loose, it could permanently dock with the satellite to provide power (R6: Recharge). Assuming a 7 percent discount rate, a servicing mission costing 40 million Euros, and a revenue stream of 10 million Euros per year, the net present value of the investment is more than 30 million Euros after the 15-year lifecycle. This analysis does not consider the flexibility of having an extra satellite on orbit in the event of other failures, which is a more difficult value proposition to quantify.

B. Assembly

1. Scenario 1: GEO Communications Satellite Enhancement

Studies have shown that installing additional reflectors and a robotic arm on a large GEO satellite can help increase the antenna area by over 50 percent (Lymer et al. 2016). This directly translates into additional customer areas served or power delivered. Assuming that the original design generated $40 million per year in revenue to the operators, a robotically assembled version could generate $60 million or more. A robotic arm capable of this activity, qualified for the GEO environment, would cost $20 to $40 million, and some additional costs would be incurred for operator training and control equipment. Nevertheless, over a 10-year span a robotically assembled version could increase owner revenues by more than $100 million. In addition, a robotic arm could perform subsequent services such as module addition or replacement, new modules having been delivered by a servicer.

2. Scenario 2: GEO Platform Assembly

A large platform in GEO for hosting multiple communications payloads would require assembly of multiple components. It might appear similar to the ISS, carrying large solar arrays at the ends of a central truss (but no provision for life support). A platform concept consists of modules totaling 14,000 kilograms, delivered to GEO by two Falcon Heavy launches and robotically assembled there. The cost would be perhaps $700 million for the platform components including robotics and $220 million for the launches, for a total of $920 million. The platform could provide 200 kilowatts of power, enough to host eight of today's high-power GEO communication payloads. A robotic servicer would be contracted to intercept payloads in their GEO insertion orbits and transfer them to the platform, whose onboard robotics would mount and connect the payloads.

A high-power GEO communications payload may cost $150 million, generating $40 million per year revenue for the operator. Since there are no launch vehicles directly addressing this class of payload, delivery to GEO would require a dual manifest, direct inject launch (for a Falcon Heavy, half the launch cost would be $55 million). The servicer operator could charge $10 million for capture of the payload and delivery to the platform. The total cost of $215 million is only about half of the cost of putting the same payload on its own spacecraft bus, for the same capability. The multi-payload platform provides power, station-keeping, and attitude control for an annual $20 million hosting fee. The payload operator has saved $200 million in capital costs but annual revenue is reduced from $40 million to $20 million, although operations costs may be reduced because operations are now the responsibility of the platform operator. The platform operator's annual revenue from hosting eight payloads would be $160 million, recapitalizing the platform cost in 6 years.

3. Scenario 3: Space Telescope

The cost of a space telescope generally increases exponentially with the diameter of its primary mirror (Stahl et al. 2013). As primary mirrors grow wider than the diameter that the fairing of its launch vehicle can support, the complexity of the whole spacecraft grows. The James Webb Space Telescope (JWST) is designed to fold into its launch vehicle fairing and unfold when it gets to space, increasing mission complexity and risk by relying on 20 sequential deployment events, 40 deployable structures, and 178 release mechanisms. JWST's primary mirror system has a diameter of 6.5 meters; future generations of flagship telescopes will have primary mirror diameters that are much larger than the maximum fairing diameter of any launch vehicle (Boyd et al. 2016). The cost of the James Webb Space Telescope is passing $10 billion, and the next generation telescope after JWST will likely follow a similar cost curve with respect to its primary mirror diameter.

A recent study explored the In-Space Astronomical Telescope (iSAT) concept (Mukherjee et al. 2019). The iSAT study team found that a telescope assembled in space removes many launch vehicle limitations, provides a more manageable risk posture, and is scalable over long periods of time depending on investment levels. The cost savings from such a telescope in comparison to a traditional monolithic space telescope comes through many paths, and the overall cost for a telescope assembled in space does not scale exponentially with its primary mirror diameter. The iSAT study concluded that, for observatories with primary mirrors 10 meters or more in diameter, in-space assembly yielded significant cost savings compared to traditional designs. There were also benefits including reduced program risks and increased scientific yields.

C. Manufacturing

1. Scenario 1: Large Area GEO Communications Satellite Antenna

The data rate that can be provided by a radio communication system is directly related to the product of the transmitter power and the area of the transmitting antenna. This directly translates into additional customer areas served or power delivered. A typical GEO satellite with four 2-meter antenna reflectors might generate $40 million per year in revenue for the operator. Manufacturing four 4-meter reflectors on orbit—too large for integration onto a satellite prior to launch—increases the potential data rate (and hence revenues) by up to a factor of four. A facility capable of building these antennas, qualified for the GEO environment, might cost $50 million, and some additional costs would be incurred for robotics to emplace the antennas in their mounts. Over a 10-year span the in-space manufactured version could increase owner revenues by more than $100 million. In addition, the manufacturing equipment could build new antenna reflectors later in the spacecraft's life, as customer patterns change on Earth. The manufacturing alternative might save the operator hundreds of millions of dollars in capital investment, by deferring the need to launch a replacement spacecraft.

2. Scenario 2: GEO Platform Manufacture

A large platform in GEO for hosting multiple communications payloads would require multiple large, lightweight components. It might appear similar to the ISS, carrying large solar arrays at the ends of a central truss (but without provisions for human presence). Manufacturing the truss on orbit is an alternative to launching pre-assembled truss segments. It can potentially reduce the number of launches required to deliver the platform components, as pre-assembled truss segments would occupy a large volume within the launch fairing even though their masses are low.

3. Scenario 3: ISRU for Propellant

In order to form a more robust and sustainable human exploration space program, the resources of the space environment may need to be used. Water found on the Moon and inside asteroids can not only help sustain human life, it can be converted into propellant to enable high delta-V missions, either to increase efficiency or to decrease the time humans spend in a deep-space environment and reduce radiation exposure (Lal et al. 2018).

Given that launch costs from Earth are falling, it is unlikely that water derived from the Moon or asteroids can be cost-effectively delivered to LEO to support propellant depots. However, a propellant depot in GEO or cislunar space could be a more effective way to support deep space operations and enable more missions at lower costs.

A recent STPI study compared several methodologies and examined potential future demand for propellant in space from human exploration programs and found that propellant derived from extraterrestrial bodies and delivered to cislunar space could beat the costs of delivering propellant from Earth (Lal et al. 2018). Only one report STPI examined claimed to be able to beat potential LEO delivery costs, but all the reports showed that asteroid-derived water could beat Earth-delivered water prices.

If a future human landing site on the Moon is near the South Pole and can derive water from the craters, it can support a propellant supply chain that will enable further exploration across the Moon and help ferry astronauts between the surface, cislunar space, and back to Earth. There are several advantages of lunar-derived water over asteroids: the technology required for a lunar water extraction system is likely cheaper and more simple than a fully autonomous asteroid mining operation; water from the Moon is significantly more available than water derived from an asteroid in an orbit with orbit transfer opportunities that occur over very long (multi-year) periods; and the water is located at the site of consumption and does not have to be ferried from another place, wasting propellant.

4. Scenario 4: Recycling

According to data from Space-Track.org, there are thousands of spent rocket bodies orbiting Earth. Orbiting rocket bodies have a total mass in the millions of kilograms, nearly half of the total mass of objects in space (Liou 2011). Each rocket body has a mass of hundreds of kilograms, mostly built of space-qualified metal alloys with well-characterized material properties. Each rocket body could be worth millions of dollars in raw materials from saved launch costs alone. This material can be transformed into a number of space products if the technology for recycling the material is developed. However, the diversity of their orbits means that significant expense would be incurred in the recycled material to the point of use.

In additional to the material savings, rocket bodies, which are typically considered space debris because they are no longer controllable, create the largest risk of a collision in space, primarily because of how large their cross-sectional areas are (McKnight 2018). A recycling enterprise could generate revenue by removing debris as well as by selling products that are manufactured from the mass of captured objects.

One challenge in the economics of recycling is the transfer of the recyclable material to an orbit where it can be recycled. Many rocket bodies are in highly elliptical orbits, which require large amounts of propellant to move into a common orbit for reuse.

D. Articulating the Value Proposition of OSAM to Decision Makers

Despite the touted advantages of adopting OSAM capabilities, and the fact that most of the required technologies are already in use, there are many uncertainties today that make articulating the value proposition of OSAM difficult, both from an individual mission perspective as well as a broader programmatic perspective. These uncertainties, while inherent in most other business or public use cases, are not typical in traditional space operations, and decision makers cannot easily navigate the strategies necessary to confidently maximize their return on value. Better decision-making tools are required to balance the many tradeoffs mission and program managers can take that will add costs up front but provide uncertain benefits in the future.

Many interviewees from satellite servicing companies with whom STPI spoke noted that satellite companies would be willing to purchase satellite services if the services existed today, but they are unwilling to commit to such services (that do not exist today) in 3 to 5 years. This “chicken and egg” problem is much more complex than a simple “build it and they will come” solution. A company will not purchase services if it does not increase profitability by reducing costs, and the mission manager of a government-funded mission will not risk the added cost for uncertain gains in utility or public benefits.

Incorporating OSAM is an example of a *real option* for satellite manufacturers and operators. Financial options are purchased so that the holder can exercise a right to buy or sell equities or other assets at a future price. Real options are purchases of physical components that may or may not be used in the future, but that add flexibility to complex engineered systems (Hassan 2005). The exercise of a real option at the design stage must consider uncertainties. A company with a fiduciary responsibility to its investors must justify spending an extra $50,000 on a fuel valve that will make refueling a satellite possible when no company currently exists to provide such services, although some are emerging. Similarly, a government agency like NASA must justify the need for propellant depots around Earth to support a Mars mission that is over 15 years away. But if that mission cannot be executed with a single heavy-lift rocket launch, the decision shifts. Without the ability to clearly articulate a demand signal, companies have been slow to adopt OSAM as part of their satellite designs, and governments and the private sector are only beginning to invest in projects that leverage OSAM capabilities. The contract by Intelsat General Corporation to use Northrop Grumman's Mission Extension Vehicle to extend the lives of two of its satellites is an early indicator of commercial OSAM interest. The U.S. Air Force is not far behind, having issued a contract to Northrop Grumman subsidiary Space Logistics to study the servicing of its GEO satellites (Strout 2019).

For most businesses, decisions about strategy—either for a servicing mission after it has experienced an on-orbit failure or for deciding to launch a new business or service—are typically made based on how it affects profitability. For government agencies, other tools like cost-benefit analysis or multi-attribute utility theory can help shape decisions. All of these decisions are made under uncertainty over the lifecycle of the mission or program, and risk-averse mission managers are more likely to choose an option with less uncertainty if the benefits are also uncertain. In OSAM, especially today, there are many uncertainties, some of which include: the uncertainty of needing a servicing mission; the availability of a contractor to conduct the servicing or repair mission; the existence of in-space infrastructure to use in standard or special operations; the utility of and availability of funding for extending the life of a mission operating nominally beyond its original lifecycle; and what the market will be by the time a mission requires or desires OSAM capabilities.

Better tools for decision making in the Pre-Phase A design process, including more advanced multi-attribute utility approaches (Ross et al. 2009; Corbin 2015), can help mission managers and company executives better understand the risks and articulate the tangible advantages for leveraging OSAM capabilities. Other tools used during the operations phases of the mission can help rank decisions that are made that modify the lifecycle of the mission to aid in fleet management. However, use of these tools requires more upfront costs, increasing the burden on private companies and necessitating changes in agency policies such as NASA's Systems Engineering Handbook. A company or agency employing such tools could better plan programs and missions to justify the needs and advantages of OSAM capabilities. If advanced decision-making tools are adopted from systems engineering research programs, OSAM is likely to proliferate faster.

While many could argue that commercialization of space could allow the second-order benefits of OSAM to proliferate to the broader space community and to the world, the literature and our interviews showed the militarization of space may in fact be a stronger driver for OSAM capabilities to develop. Military satellites are more likely to be expensive enough to justify assembly in space, or repairing and require a repair mission on a short timescale. Military satellites are more likely to execute unplanned orbit changing maneuvers and therefore require refueling; building the supply chain to execute regular refueling missions would then make satellite maneuvers more common, leading to both a more responsive military satellite enterprise and an infrastructure base that can be leveraged for other applications. If regular maneuvering, refueling services, and infrastructure use become common, incorporating those elements in the concept selection phase of a mission will be easier. Military systems are also already likely to use complex concept selection methods to make decisions under uncertain operational contexts and be able to better articulate the lifecycle benefits from serviceability and other space infrastructure. These missions can afford the upfront costs required in Pre-Phase A studies to consider the trade space of possibilities, whereas a private company may not wish to spend the necessary resources so early in the design lifecycle.

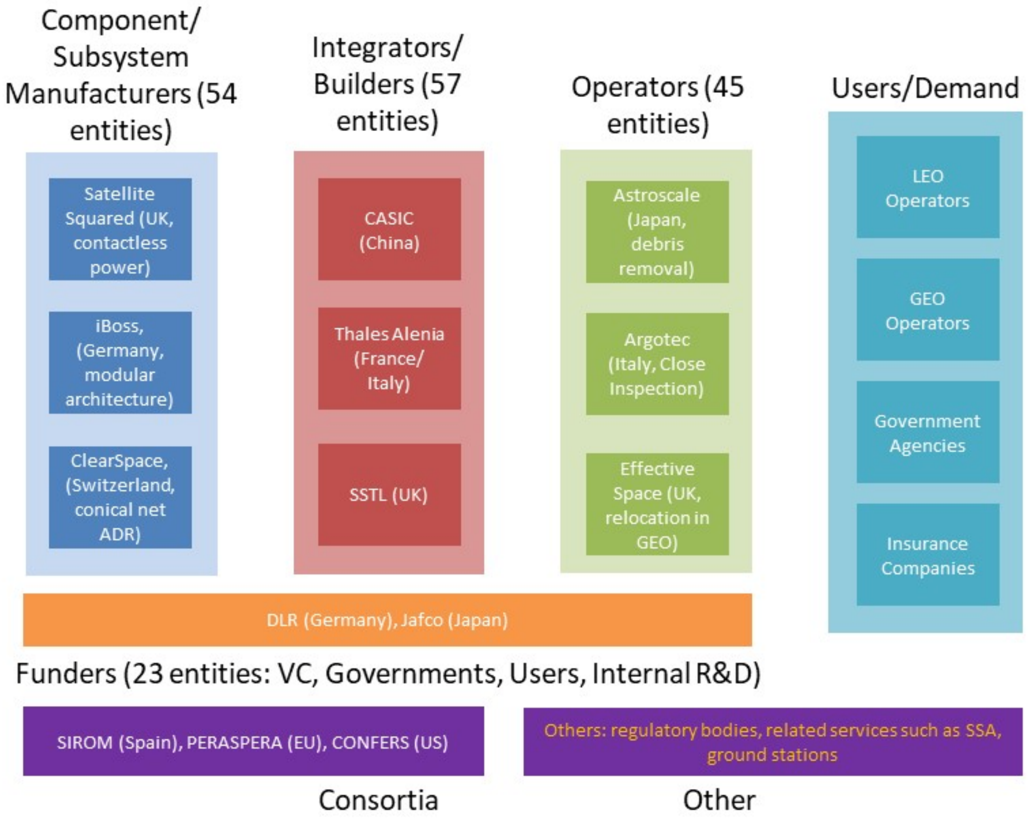
Based on STPI’s interviews, it appears that no single entity has the mission, resources, or long-term vision to implement the full range of OSAM capabilities, or push OSAM to become the future core of space operations, but in principle nearly all entities involved in space can benefit from OSAM and its emergent capabilities. In the following chapter, we will examine how countries around the world are investing in this area, and exploring its usefulness for science, exploration, commercial and national security missions.

4. Global Activities and Partnerships in OSAM

This chapter summarizes ongoing global activity in OSAM. While the focus of this report is primarily on international OSAM entities and their activities, we discuss U.S. entities for context, and as they relate to major activities, international partnerships, and market forces that affect OSAM development.

A. Descriptive Statistics - Global OSAM Entities

In order to better understand global OSAM activities, STPI developed an OSAM ecosystem model to help classify how organizations fill different roles. STPI identified six distinct ecosystem roles: component providers, system integrators, satellite operators, users, funders, and providers of related services. A single entity can fulfill one or more of these roles and evolve over time to play several roles.



Note: Organizations in parentheses are illustrations; the full database is available on request

Figure 4-1. OSAM Ecosystem Model

Next, STPI developed a database of entities that have publicly discussed current or near-future involvement in OSAM. STPI had many criteria for determining which entities were included versus which ones were not. For example, we could not include every component manufacturer engaging in development of space robotics technologies, but companies that specifically aimed to provide hardware for satellite servicing and assembly were included. Providers of related services like SSA were included only if they had expressed specific interest in providing servicing to aid other OSAM entities; we did not include every provider of SSA data. Entities that shape the OSAM market, such as insurance providers who are actively pushing for remote survey as an incentive to reduce premiums, were not included. Companies that we thought were too immature were not included. Potential users were not included unless they were engaged in other activities (i.e., Intelsat was not included because it is only a user of OSAM services, but DARPA is because it is also acting as a funder and integrator for technology development), although we did engage with potential users to understand their reasons for purchasing OSAM services. Companies engaged in consortia related to OSAM were not included unless they were intentionally developing OSAM systems and not sending representatives to better follow trends and gauge interest.

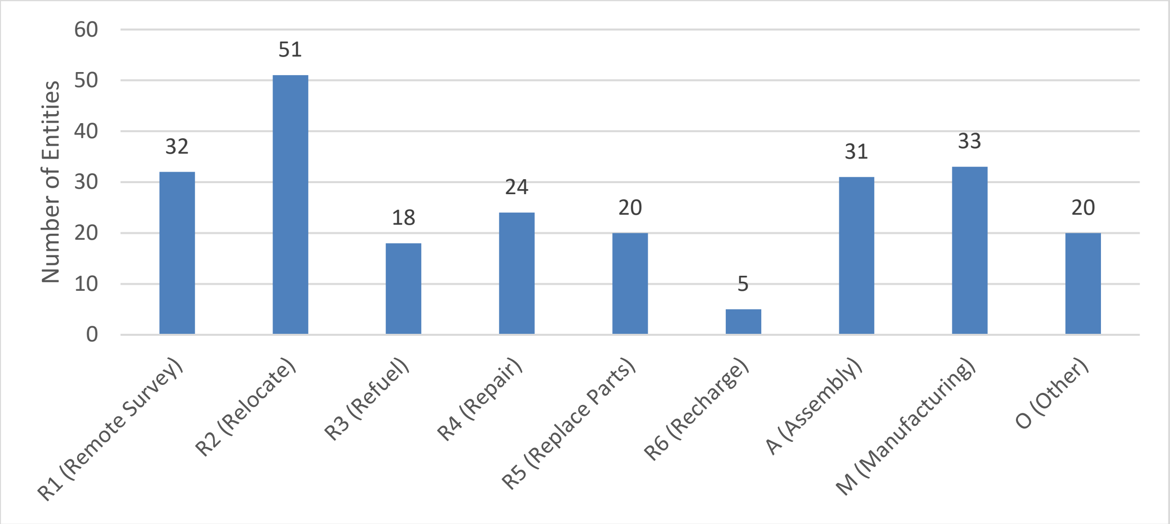
STPI identified 115 organizations around the world that met the above criteria. These organizations were characterized by ecosystem role, country, sector (private, government, or academic), and OSAM capability area (R1: Remote Survey; R2: Relocate; R3: Refuel; R4: Repair; R5: Replace Parts; R6: Recharge; A: Assembly; or M: Manufacturing).

Figure 4-2 shows the distribution of OSAM entities by country. The plurality of the organizations are based in the United States (51 entities; 44 percent), followed by Russia (12 entities; 10 percent) and the United Kingdom (9 entities; 8 percent). With the exception of some European entities, all multinational entities were classified by where an organization is headquartered or the location in which it is primarily associated.

Figure 4-3 shows the distribution of entities by the OSAM capability area in which they are engaged. Since entities are often engaged in more than one capability area, the sum of the data shown in the figure is greater than the number of entities in the database. R2: Relocation services is the capability area that has the most entities engaged, while R6: Recharge is the area with the fewest. *Other* includes activities that support OSAM but fall outside the identified capability areas, such as those of standards-developing organizations.

Source: STPI Database

Figure 4-2. Distribution of Organizations by Country

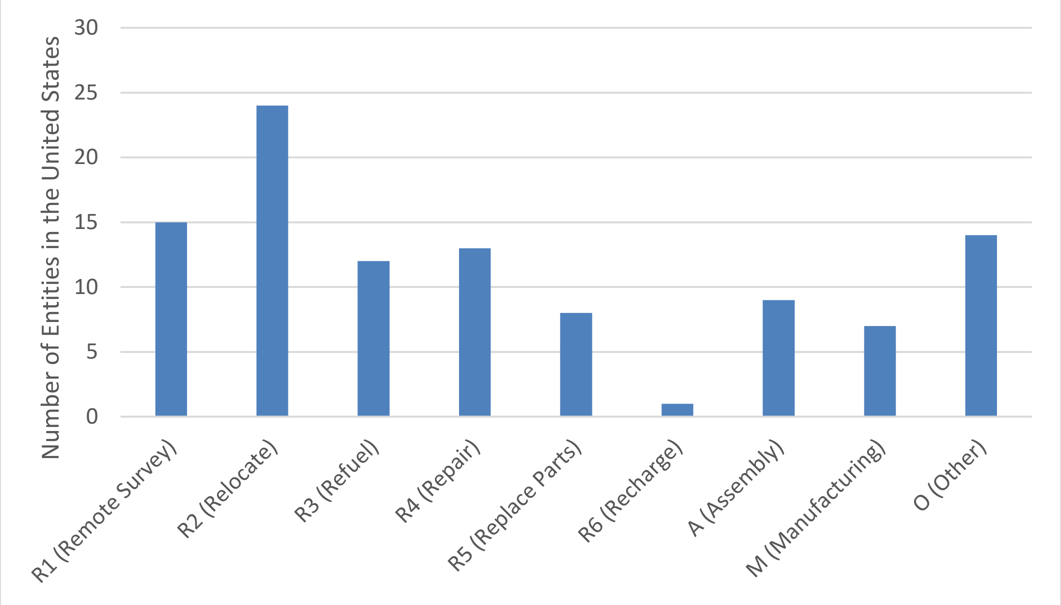


Source: STPI Database

Note: *Other* includes activities that support OSAM but fall outside the identified capability areas. Examples include standards-developing organizations and consultants.

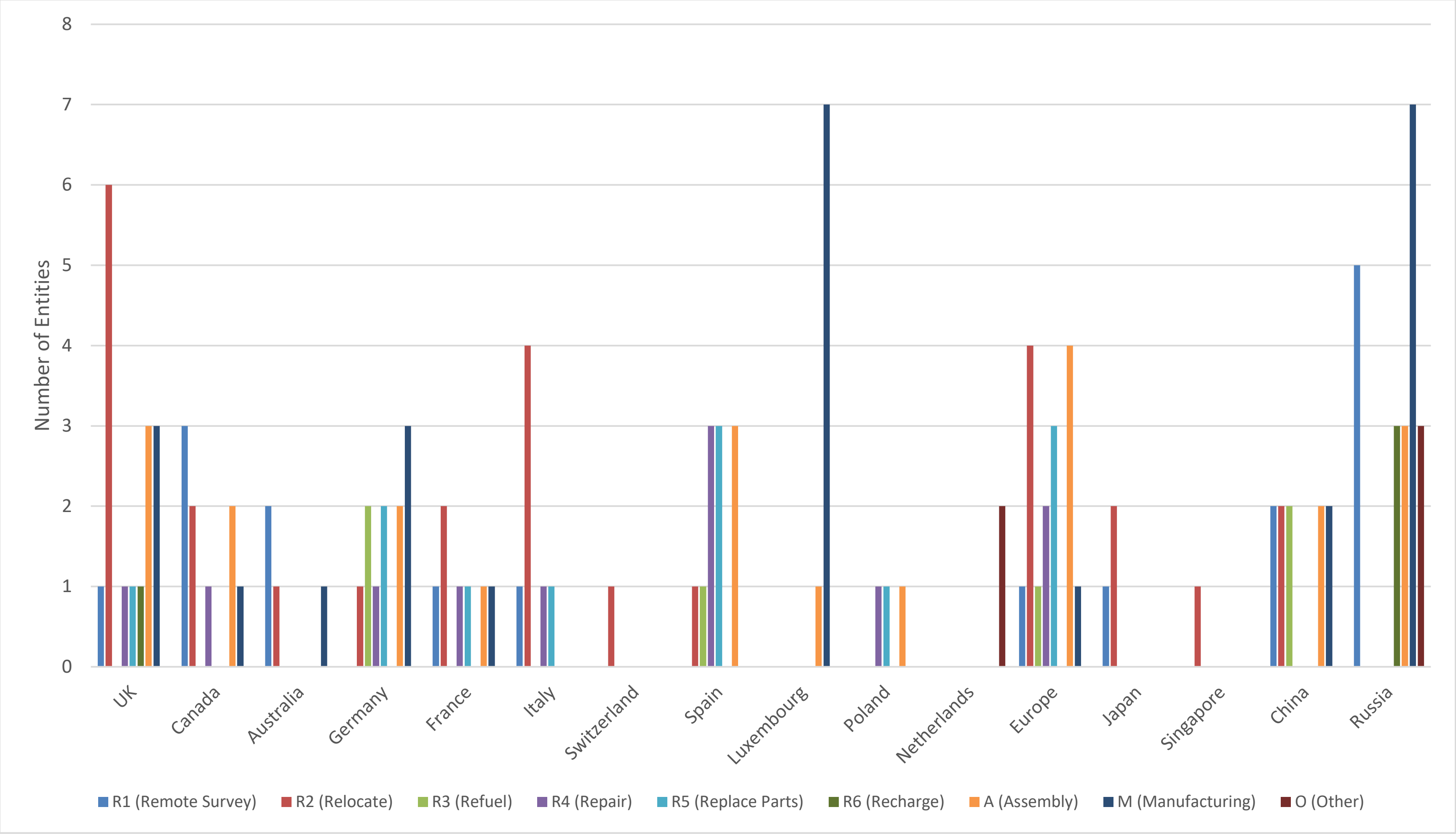
Figure 4-3. Organizations by OSAM Area

Within the United States, 24 of 51 entities are involved with relocation services (Figure 4-4). France and other countries in Europe have a similar distribution. Several other countries are more specialized: both of Japan's and six of the United Kingdom's nine entities are involved in relocation services; all seven of Luxembourg’s entities are focused on manufacturing; Russia’s entities focus on remote survey and manufacturing capabilities (Figure 4-5). In the following figures, countries are organized, from left to right, by Five Eyes, then other European and allied countries, and finally other global competitors.



Note: An organization can be classified into multiple categories.

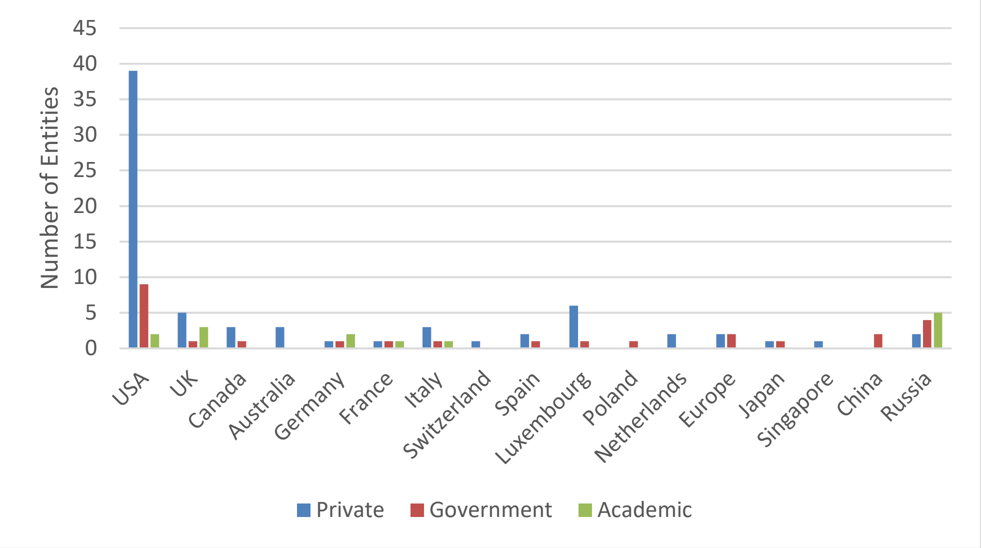
Figure 4-4. Organizations by OSAM Area: United States



Note: An organization can be classified into multiple categories.

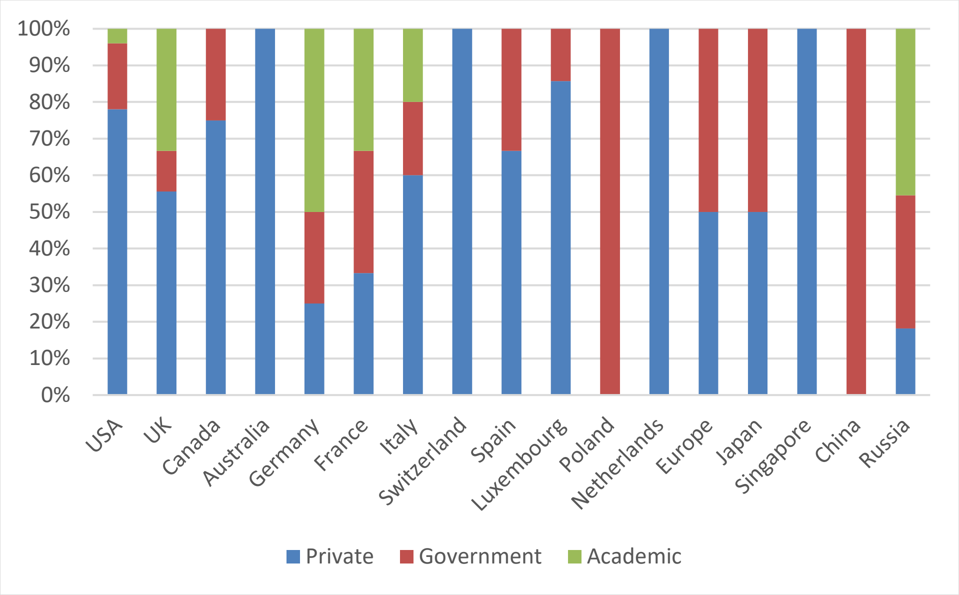
Figure 4-5. Organizations by Country and OSAM Area: Excluding the United States

Figure 4-6 shows that the majority of entities working on OSAM are private (74; 64 percent). While the U.S. has nine government entities working on OSAM, most countries only have one entity (the national space agency) involved. China is an outlier; all Chinese OSAM activity comes from government entities (Figure 4-7). In addition, France, Italy, Russia, the United States, and the United Kingdom have academic entities involved with OSAM work, most commonly working on research and development.



Note: An organization can be classified into multiple categories.

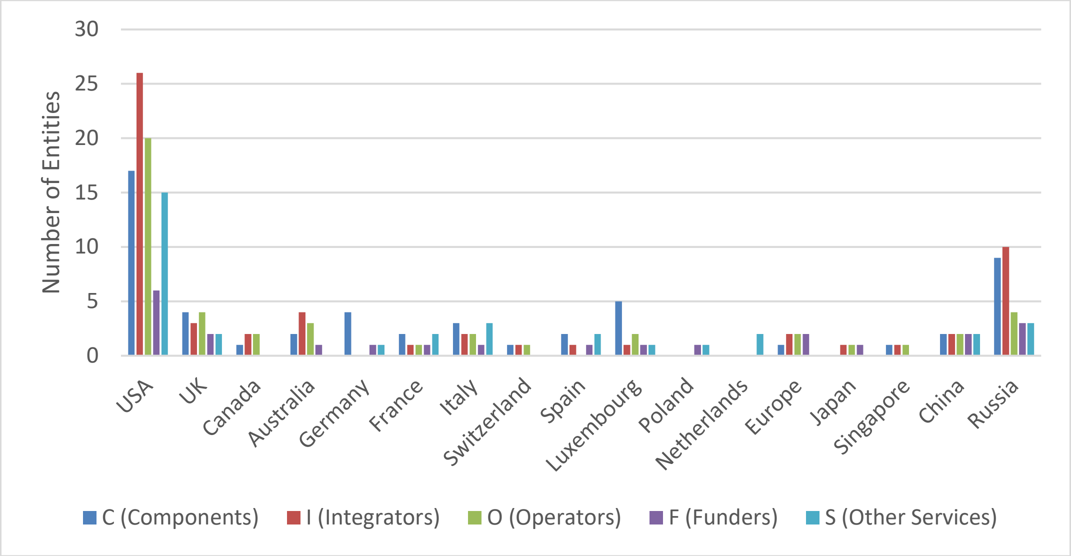
Figure 4-6. Organizations by Country and Entity Type



Note: An organization can be classified into multiple categories.

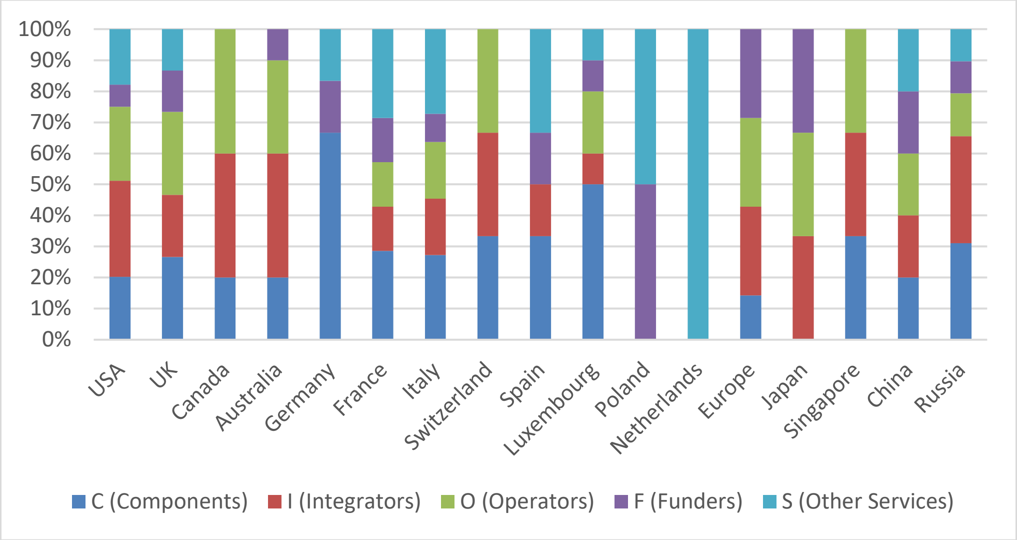
Figure 4-7. Organizations by Country and Entity Type as a Percentage

In the United States, we found at least six entities involved at every level of the ecosystem, from component manufacturers to funders and supporting entities (Figure 4-8). Unsurprisingly, given the relative lack of OSAM entities in other countries, no other country approaches this level of diversity across the OSAM ecosystem. However, Australia, France, China, and Russia all have at least one entity in each category, while Europe is only missing supporting entities. Some countries like Poland and the Netherlands with smaller space programs have entered the OSAM ecosystem through funding and standards organizations (Figure 4-9).



Note: An organization can be classified into multiple categories.

Figure 4-8. Organizations by Ecosystem Role



Note: An organization can classified into multiple categories.

Figure 4-9. Organizations by OSAM Area as a Percentage

It is important to note that the number of organizations is not necessarily a measure of a country’s strength in OSAM. In other words, China—with two organizations working on OSAM—could be as strong as the United States with 51 organizations working OSAM. Section B provides more qualitative detail on country capabilities—to the extent the information was available through the interviews or the literature. More detail about each country we examined closely can be found in Appendix C.

B. Global Activities in OSAM

As Section A shows, there are organizations engaged in OSAM-related activities in 17 countries around the world, as well as at multinational European entities. As a reminder, the focus of this report is international, and activities of U.S. entities are listed either for context or because they are involved in international collaborations or seek international customers. Individual country case studies are included in Appendix C. In this section, we highlight capabilities by each of the eight OSAM capability areas. A summary of our assessment of OSAM capabilities by country is shown in Table 4-1.

1. R1: Remote Survey

As discussed above, the United States is the most engaged in remote survey with 15 organizations involved in R&D or related work. Russia follows the United States with five organizations taking part in remote survey, Canada with three, and Australia and China each with two. The majority of the countries included in our database have at least one organization engaged in remote survey.

Long-standing (since the 1980s) government and private investment is a contributing factor to the United States’ leadership in remote survey. Many U.S. companies have an interest in or are in the process of seeking licenses for imaging, and intend to use the data for insurance and other reasons discussed in Chapter 2. One of

Company Highlight #1: HEO Robotics, Australia

HEO Robotics, founded in 2016 and headquartered in Australia, is a small start-up that uploads a software package onto third-party host satellites that have imagery capabilities to provide remote survey services to clients without ever launching its own satellite. This activity would be illegal in the United States, but Australia does not have a remote sensing policy that prohibits such activity. As a result, they have a competitive advantage for some remote survey products, though their ability to obtain imagery is limited to times when the client and host satellite cross near each other. This imagery is higher quality than what can be obtained from ground-based SSA but not as good as dedicated satellites conducting RPO. Nevertheless, HEO presents an innovative business case that cuts costs compared to American counterparts because it leverages a regulatory environment that is more permissive than the United States’ remote sensing policy. HEO only partners with Australian host operators, but similar models could be employed by other countries. Cybersecurity may be a concern for concepts like this, as uploading imagery software requires high levels of trust between the servicer and the host satellite.

these commercial companies is the startup Chandah Space Technologies that has obtained a license from the National Oceanic and Atmospheric Administration for general SSA but also specifically for imaging GEO satellites. Chandah envisions selling the imagery to space insurers to adjudicate claims and to manufacturers to assess changes or damages on orbit.

Company Highlight #2: Argotec, Italy

The Italian company Argotec is expected to launch a small satellite with the capability to conduct R1: Close Inspection services within the bus of a larger satellite to conduct remote survey operations in deep space. For both the ESA DART mission and NASA’s Artemis EM-1 mission, as the large spacecraft nears the location of its mission, the Argotec small satellite is expected to eject from the main craft to photograph and inspect the mission and provide validation services from a distance. The shoe-sized ArgoMoon satellite uses radiation resistant components, not typical for most nanosatellites. Argotec is the first company to test CubeSat “drones” far away from Earth, in the extreme conditions of a translunar orbit. Technologies like these may make it more difficult to track remote inspection activities and easier to hide payloads on larger buses.

U.S. entities have also incorporated remote survey technology onto spacecraft needed for servicing missions. In October 2019, Northrop Grumman launched Mission Extension Vehicle-1 (MEV-1), which is intended to service Intelsat-901 (it docked with the satellite in February 2020); its rendezvous sensors included cameras suitable for remote imaging and ultra-close inspection (Henry 2019a). Our interviews revealed that many companies in the OSAM sector broadly, not just in the realm of remote survey, are watching the evolution of the MEV before initiating activity in the area. Companies include both startups and large contractors such as Thales Alenia.

While we found that the United States has the most commercial companies working on remote survey, most of the countries included in our database are also active, though to a lesser extent. Russia successfully tested a servicing satellite for remote inspection in 2017 that is capable of approaching orbiting vehicles and inspecting them (Valchenko et al. 2017); Russia has also alarmed the international community by engaging in RPO that could be for remote survey or some other form of intelligence gathering without notifying other satellite operators first (Adamczyk 2020). China has demonstrated remote observation in the context of other satellite activities though few demonstrate remote observation alone (Weeden 2008). In Australia, the startup HEO Robotics has developed a software package, which it can load onto other operators’ satellites to capitalize on high resolution cameras already in orbit (see Company Highlight #1). The Italian company Argotec has partnered with NASA to provide remote survey of two deep space missions in order to monitor activity and validate mission performance (see Company Highlight #2). Canadian startup Northstar is also developing plans to offer remote survey services.

Of the different components of OSAM, R1, remote survey, has the most technological maturity, in large part due to the relative simplicity of inspection as a service. The technological maturity of remote inspection also explains why most countries that have some form of OSAM activities have at least one entity working on remote inspection.

To our knowledge, no commercial entity is currently capable of obtaining ultra-close survey imagery, other than that from Northrop Grumman's MEV that is incidental to docking. The DARPA-funded RSGS spacecraft will be capable of ultra-close imaging using its end-of-arm cameras (Roesler 2017). The Chinese satellite Shijian-17 has operated within 10–15 km of other spacecraft, most likely guided optically, and so is likely to be able to obtain exquisite remote survey imagery (Clark 2018).

Company Highlight #3: Effective Space

Effective Space, a startup developing a satellite servicing system, was founded in Israel, but later licensed its fleet through the U.K. Space Agency, procured its insurance through Marsh We, a U.K. broker, used the Spanish, French, and other European entities as suppliers of mission-critical components, tested its technical capabilities at a Spanish facility, contracted with Israel's IAI to manufacture their small satellite servicers, and has been contracted by a commercial operator for two servicing missions, with expected revenues reaching $100 million. Effective Space is aiming to initiate commercial operations in 2021 or 2022. Investing and operating in multiple countries may provide stability to companies but could create concerns over funding sources, conflicts of international interest, and technology and intellectual property theft.

2. R2: Relocate

For OSAM, progress in relocation is primarily spearheaded by government entities and a number of private companies in the United States, Europe, Australia, and Japan. Unlike R1, relocation is a more sophisticated capability for countries to accomplish due to the technological complexity required to accurately target, rendezvous with, grapple, and move satellites and debris in orbit. The funding required interested companies to participate and demonstrate active debris removal and end-of-life servicing serves as a barrier to entry.

The United States leads global activity in relocation, with 24 organizations involved in R&D or related work. A handful of European countries follow behind the lead of the United States, including the United Kingdom with 6 organizations, Italy with 4, and France with 3. Of the 17 countries in our database (including Europe), we identified Russia as the only country without an organization participating in relocation.

Many private companies, academic institutions, and government institutions have made progress on the R&D and technology needed to relocate spacecraft. In February 2020, Northrop Grumman's MEV-1 docked with a GEO satellite, brought Intelsat 901 to operational service, and is designed to maintain its orbit for several years; however, it could just as easily thrust continuously to achieve relocation (Northup Grumman 2020).

Our interviews revealed that many larger companies in the OSAM sector are watching the evolution of the MEV before initiating activity in the area, though some smaller companies have begun pursuing similar capabilities. The UK-based company Effective Space is offering GEO satellite deorbiting and life extension services using its Space Drones to grapple, then relocate the target. (see Company Highlight #3). Canada's Orbuta Space Solutions is a startup that aims to provide payload relocation services in the future.

Internationally, more organizations are invested in relocation to address growing concerns with orbital debris and end-of-life servicing. Many European entities have an interest in orbital debris removal. ESA, under its Clean Space initiative, had been contemplating a debris removal mission known as e.Deorbit. The mission concept was fully funded in November 2019, redefined as a robotic space servicing vehicle capable of many different missions, including relocation and space debris removal. ESA has also partnered with the Swiss company ClearSpace to remove a 265-pound piece of an old ESA rocket body orbiting at 310 miles. The mission is planned for launch in 2025 (ESA 2019).

Australia's Exodus Space Systems aims to build a "street sweeper" using its Kinetic Solution for Space Debris (KiSSD) technology to conduct active debris removal (ADR). The company believes its ADR technology is an order of magnitude better than competitors', but does not appear to have made a description of the concept of operations of this method public, and as of this writing the company has not presented a timeline for operations to start.

Though there are fewer organizations in Japan working on servicing in comparison to the United States and Europe, Japan's focus on space sustainability and orbital debris mitigation makes it an important player for servicing and relocation with both the Japanese government and those in the private sector building technology and partnerships needed to carry out active debris removal and end-of-life satellite servicing. This includes the orbital debris removal company Astroscale, which is developing a vehicle specifically for the removal of space debris.

3. R3: Refuel

The United States is the most involved in in-space refueling, with 12 organizations involved in R&D or related work. China and Germany each has two organizations involved in activities related to refueling, while the remaining countries in our database do not have any organizations participating in R3.

In the U.S. private sector, several companies are working on technologies and capabilities that fall under R3: Refuel. The startup OrbitFab is developing technologies to store fuel in orbit in hopes of having fuel depots in space. It was the first company to supply water to the ISS (Etherington 2019), which the company sees as a key first step to in-space propellant storage and production. Other companies such as Hoffer Flow Controls and Moog sell flow control devices necessary for refueling.

While no European entity is explicitly developing a satellite servicer with the intention of refueling a client, the German government and a private company, iBOSS GmbH, have cooperated to develop a standardized interface to allow the transfer of data, power, and fuel between two satellites. The European Commission is also developing its own standardized interface to allow the transfer of data, power, and fuel, Standard Interface for Robotic Manipulation of Payloads in Future Space Missions (SIROM), in coordination with a number of government and private entities in Europe. A standard interface is a critical enabling technology for refueling services.

In recent years, China has conducted two major demonstrations of refueling satellites and spacecraft; both demonstrations have included research into supporting technologies needed to make progress in long-term on-orbit storage of fuel and missions that involve multiple satellites (Xinhua 2016a; Xinhua 2017; United Nations Office for Outer Space Affairs [UNOOSA] 2018; Zhang et al. 2018; Zhang 2018; Yu et al. 2018).

Globally, for a few reasons fewer organizations are investing in refueling. Investment in refueling services, such as repairing and replacing parts, suffers from a chicken-and-the-egg problem: most satellites in orbit were never designed to be refueled, so operators have no reason to invest in or even the ability to enable refueling services, which constrains the technological and market growth of refueling. The relative immaturity of refueling due to this lack of funding makes it even less appealing for operators when considering potential investments. In addition, and in comparison to R1 and R2, where most OSAM activity resides, R3 requires greater technical competence. NASA has conducted refueling experiments on the exterior of the ISS. The Robotic Refueling Missions tested the ability of the ISS robotic arm to manipulate the kinds of valves that are found on unprepared satellites, and then to transfer fuel to them (NASA n.d.). The complexity of these operations reinforces the slow pace of adoption of refueling. Most of the more advanced use cases of OSAM in R3–R6, A, and M are groundbreaking capabilities that have never been accomplished before, even on the ISS, so the substantial time, technical expertise, and money that must be invested to develop these areas remains a barrier.

4. R4: Repair

The United States leads R4, with 13 organizations participating in activities related to repair. We also identified three entities in Spain and two multinational European entities working towards repair services. In addition, we identified one organization participating in R&D or relevant activities required for repair in each of the following countries: Canada, France, Italy, Germany, Poland, and the United Kingdom.

In the United States, both government and industry are active in repair capabilities. The DARPA RSGS spacecraft, when launched in 2022, will have repair as one of its four baseline capabilities. RSGS will be equipped with two robotic arms capable of applying the precise forces needed for safe and effective repairs. Tools on the arms can be exchanged for specific repair needs. In the RSGS partnership, after initial testing, DARPA is expected to transfer ownership of the dexterous robotic servicer to Space Logistics (the wholly owned subsidiary of Northrup Grumman) for commercial operations (DARPA 2020). In industry, Tethers Unlimited, with Canada’s Maxar Technologies, is developing robotic arms specifically for servicing, assembly, and manufacturing. Maxar’s American subsidy, Space Systems Loral, possesses the technologies required to conduct a range of satellite servicing. However, Space Systems Loral recently backed out of the DARPA mission, stating that it did not see enough of a market for its investments in satellite servicing, and was replaced by Space Logistics (Erwin 2019a).

European entities working towards repair services are largely participating in missions separately sponsored by the European Commission and ESA to develop the robotic capabilities necessary for on-orbit repair.

Repair services are fairly undeveloped, both with respect to the technological maturity of the required subsystems as well as the maturity of the market. Several entities, particularly iBOSS GmbH from Germany and the European multinational company Airbus, are developing modular systems to allow for assembly of space structures. If such systems were to become the norm of space architectures, then simply removing a dysfunctional module and replacing it with a new module may still be considered repair. Therefore, the future of unique repair services is synergistic with the development of modular systems and assembly.

5. R5: Replace Parts

The United States has the most entities working on replacing parts, with eight organizations. Outside the United States, we identified three multinational European entities (Airbus, the European Commission, and ESA) working on replacement of parts. In addition, entities in six European countries are also taking part in replacement of parts: Spain has three organizations; Germany has two; while France, Italy, Poland, and the United Kingdom each has one.

The Hubble Space Telescope is the most well-known example of a space system that was designed to be serviced. Although the repair missions were done by humans rather than autonomous robots, the modular payloads on Hubble were designed to be switched out easily. In the United States, companies like Altius Space Machines, Saturn Satellite Networks (who recently bought Novawurks), and Tethers Unlimited are all working on modular systems to make plug-and-play capabilities in space a possibility, though most of these organizations would classify themselves as on-orbit assemblers rather than servicers. Many other organizations are working on innovative modular systems, which could easily be spun into satellite servicing activities.

There are no European entities working specifically towards being able to replace parts on orbit. Germany's iBOSS GmbH, in partnership with the German space agency, has developed a building block method of satellite design and construction. While the primary focus of such systems is to enable on-orbit assembly, the same technology is designed to also be used to replace one block with another in order to repair or upgrade the satellite. The modular pieces, with iBOSS's standard interface on each side, can contain an individual subsystem. These pieces can easily be connected and disconnected using robotic arms, simplifying both assembly and repair by replacing parts.

Other efforts to develop capabilities to replace parts on orbit in Europe are spearheaded by the European Commission and by ESA. Each sponsors consortia of European organizations, which are working on the technical subsystems necessary to replace satellites parts after launch. However, while these efforts focus on developing robotic systems to enable replacing parts, they also consider general interactions between a servicer and a client satellite, so are also applicable to repair and assembly operations.

Despite being identified as a unique realm of satellite servicing by NASA, replacing parts overlaps heavily with repair and assembly as on-orbit activities, in terms of both technology prerequisites and the value that can be derived from such applications. This overlap is reflected in the near complete lack of part replacement-specific activity.

6. R6: Recharge

Russia, led by its Ministry of Defense and RSC Energia, leads global activity in recharging with three organizations involved in R&D or related activities. The United Kingdom and the United States also have some limited activity. The remaining countries in our database were not found to have organizations engaged in R6: Recharging.

RSC Energia, in partnership with A.F. Mozhavsky Military-Space Academy, has conducted a practical experiment for transmitting power between satellites or between the ground and a satellite as part of an effort to develop orbital recharging stations.[7] These stations can provide capabilities that enable satellites to be smaller in size and receive power when they are operating in Earth's eclipse. The Academy hopes to launch several dozen of these satellites. Russia claims that these capabilities will be used to maintain operations of Cospas-Sarsat, a treaty-based international satellite search and rescue program, but it is unclear whether those satellites are designed to receive power like this.

The UK-based startup Satellite Squared is aiming to provide remote recharging services, but is still in the early stages of its development. Their plan is to use a reflective

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[7] Translations use the term "orbital gas stations," but these platforms would provide electric power, not propellant; to avoid confusion, STPI refers to them as recharging stations.

concentrator to raise the solar flux on another satellite's solar panels. The company is relatively young and could switch to power beaming technology in the future.

Recharging as a service is being pursued by a small number of entities, even relative to OSAM as a whole. However, the capability to do so is relatively easy in comparison to other OSAM capabilities, and it would not take as much R&D effort for a country to gain this capability and use it for strategic purposes.

7. Assembly

Having assembled the ISS on orbit, the United States has the most organizations involved in on-orbit assembly, leading global activity with nine organizations. Of the countries in our database, Russia, Spain, and the United Kingdom follow the United States with three organizations engaged in assembly, while Canada, China, and France each has two, and Luxembourg and Poland each has one. Three multinational European entities are also working towards on-orbit assembly.

As mentioned above in R5: Replace Parts, several U.S. private companies are engaged in technological efforts related to on-orbit assembly, including Altius, Saturn, and Tethers Unlimited. Axiom Space wishes to assemble a private space station and has announced it will send three private passengers to the ISS aboard a Dragon capsule (Shieber 2020). Made in Space is partnering with Northrop Grumman to demonstrate truss assembly capabilities, with an end goal to be capable of assembling kilometers-long structures.

The satellite manufacturer Space Systems Loral, a U.S. subsidiary of the Canadian company Maxar Technologies, has a robotic reflector assembly technology called Spider that will demonstrate spacecraft components being robotically assembled and reconfigured while on orbit. The technology is being readied for flight under NASA's Tipping Point technology program. Spider is intended to fly on the NASA Restore-L mission in 2023 (Maxar 2020).

China plans to use on-orbit assembly to create its next space station, the Tiangong Space Station, in 2022. More than 10 missions are planned in the next 3 years to assemble the station in orbit (Space Daily 2020).

Airbus launched its Bartolomeo module to the ISS in March 2020. The module is based on principles of modular design to enable assembly of a test-bed for in-space testing and experimentation.

Most other entities working in assembly are attempting to provide critical subsystems to integrators. Canada and Germany, through MDA and the German space agency, have long provided expertise in robotic systems, including for use during assembly operations. The Canadian Space Agency provided Canadarm 1 for the Space Shuttles, Canadarm 2 and Dextre for the ISS, and expects to provide Canadarm 3 and other capabilities for Gateway. In addition, the German private company iBOSS GmbH and the European Commission-funded SIROM consortium aim to provide standardized interfaces to allow mechanical interfaces with power, data, and thermal energy flow.

Russia has a long history of developing equipment capable of assembling parts in space. The Strela cranes are four Russian-built cargo cranes currently on the ISS, though they do not have as much capability as Canadarm 2 and Dextre. The older Stork arm on the Buran was 15 meters long and could operate in three planes with six rotational degrees of freedom. STPI did not find any sources on what new space robotics capabilities in which Russia is engaged or how they could be applied to on-orbit assembly.

The potential for on-orbit assembly to create currently infeasible systems in space, including larger telescopes and gossamer structures, makes it appealing, despite the inherent technical complexity. This complexity has proven prohibitive for smaller entities to pursue on-orbit assembly alone. Assembly is the OSAM capability with the greatest number of hopeful subsystem providers entering the market.

8. Manufacturing

Luxembourg, Russia, and the United States lead global activities in on-orbit manufacturing. We identified seven organizations involved in R&D and related activities in each country, while the United Kingdom follows with three organizations and China follows with two. Canada, Australia, France, and Germany each has one entity involved in activities related to in-space manufacturing. ESA also has ongoing activity in this area.

U.S. companies are by far the most advanced in on-orbit manufacturing. Made in Space was responsible for the first 3D printer in space. It was delivered to the ISS in 2014, and the first components were returned to Earth in 2015. Made in Space has developed a truss manufacturing technology (that can be used to autonomously construct reflectors, communication antennas, and other complex structures) called Archinaut. The technology is being readied for flight under NASA’s Tipping Point technology program. Archinaut is scheduled to reach orbit around 2023. Made in Space also has other 3D printing activities underway. For example, its VULCAN system is expected to produce “high-strength, high-precision polymer and metallic components on orbit with comparable quality to commercially-available, terrestrial machined and inspected parts.”

Other U.S. companies are active in on-orbit manufacturing as well. Tethers Unlimited has delivered its Refabricator device to the ISS. Refabricator uses waste plastic as feedstock for 3D printing, acting as a recycling system. Tethers also has demonstrated a device called “Trusselator” which builds long stiff trusses from carbon fiber feedstock. Nanoracks is developing technology to recycle spent upper stages of rockets, including welding technologies to break the craft into smaller parts. Space Tango is engaged in a number of in-space manufacturing projects, though the majority of them are for products used on Earth rather than in space. Many efforts in the United States are underway to research ISRU, though most of those are not mature and are not making a profit on commercial contracts alone.

On-orbit manufacturing of small tools from polymer feedstock has been demonstrated on the ISS. In addition to the development of the 3D printer technology, NASA has conducted evaluations of the quality and reproducibility of these manufactured components. Extensions of this work include the use of a broader range of feedstock materials and expanding to larger manufactured components.

In Russia, RSC Energia has partnered with Tomsky Polytechnic University to create the first 3D printed Russian nanosatellite. Although this satellite was printed on the ground, the goal is to be able to produce them in space so they can be deployed on-demand. They are also planning to send a printer to the ISS. The private company 3-D Bioprinting Solutions, backed by investment from INVITRO, developed Organaut, a biomedical 3D printer that was launched to the ISS in 2018. It is the world's first magnetic bioprinting experiment, and it is intended to print cartilage and thyroid glands of mice as a test of its capabilities. 3-D Bioprinting hopes to keep the printer operational for 5 years.

In 2016, China conducted its first on-orbit 3D printing experiment using composite materials (Chinese Academy of Sciences 2016). In 2018, China 3D printed ceramic molds on orbit (Xinhua 2018). These demonstrations were not ready for practical use in space, though it is not clear what progress China has made since then.

The other entities worldwide we have identified as working on in-space manufacturing are still in early stages of this work, or else are supporting those efforts in Russia. Many terrestrial additive manufacturing companies in Australia and New Zealand have expressed to their space agencies interest in developing applications for space use, but all are in early stages and STPI was unable to gather any information on them.

Despite the relative immaturity of in-space manufacturing, many entities around the world are engaged in research activities related to ISRU. Asteroid mining companies such as Deep Space Industries and Planetary Resources were bought out by other companies before developing any large-scale equipment to extract resources from asteroids, though other companies like TransAstra are still active in developing concepts. Russia and China have partnered to develop drills to dig into the lunar surface. Three German companies are engaged in Project MOONRISE, a consortium funded by the Volkswagen Foundation and the European Union's Horizon program with a goal to melt lunar dust into rigid shapes. University research programs around the world, including the United States, China, Russia, Germany, South Korea, Japan, and the United Kingdom, have attempted to address some aspects of ISRU. However, it is unlikely that ISRU will be a reality outside of U.S. Government activities within the decade.

The extremely difficult nature of in-space manufacturing, as well as the relative infancy and technical breadth compared to servicing and assembly, makes it the least technically developed of all of the OSAM areas. The potential payoff from successful missions has attracted many to invest substantial time, money, and research effort into developing in-space manufacturing capabilities, though it may take a decade or more before on-orbit manufacturing becomes a truly transformative space capability.

C. State of Technology Development by Country

Chapter 2 introduced 23 technologies underlying OSAM capabilities, and assessed which ones are critical (C), desirable (D), or enabling (E) for specific OSAM capabilities. Some technologies such as propulsion apply to all OSAM capabilities, and others such as intra-spacecraft mobility are specific to a single OSAM capability area such as assembly. In Table 4-1, we provide our best judgement of the state of affairs for each technology area for eight countries/regions of interest: China, Russia, Japan, Germany, the United Kingdom, the European Union, Canada, and Australia. A rough assessment is made of U.S. capabilities, but only as a reference. The table shows that global capabilities are relatively even across countries.

Table 4-2 builds on the technology assessment, and qualitatively summarizes country capabilities by OSAM areas. The interesting observation here is that countries may have the underlying technological capacity, and yet not engage in OSAM activities. The table shows the United States having activities across the board in all OSAM areas, but other than remote survey, hardly any other country is *currently* engaged in them.

Table 4-1. Level of Advancement in Core OSAM Technologies for Servicing by Country

OSAM Technology	Area	US	CN	RU	JP	DE	UK	EU	CA	AU
Rough-Control Propulsion	S, A, M	4	4	4	4	4	4	4	4	4
Fine-Control Propulsion	S, A	4	4	4	4	4	4	4	4	2
Guidance, Navigation, Control	S, A	4	4	4	3	2	2	4	4	0
Automation	S, A, M	4	4	3	3	3	3	3	4	0
AI/Machine Learning	A, M (S)	2	1	1	0	1	1	1	1	1
Computer Vision	S, A	4	2-3?	3?	?	2	2	2	4	0
Basic Robotic Arms	S, A, M	4	3-4?	4	2	4	3	4	4	0
Precision Manipulators	S, A (M)	0	0	0	0	0	0	0	0	0
Intra-Spacecraft Mobility	A, (S)	4	2?	2	2	3	2	3	4	0
Standardized Interfaces	S, A, M	4	4	4	4	4	3	4	4	0
Modular Payloads	A, S, M	3	1?	2?	1?	3	3	3	3	1
Norms of Behavior	S, A (M)	3	1	1	1	2	3	3	2	0
Cutting Tools	M, S, A	3	2?	2?	0	1?	0?	0?	0?	0
Space Welding	M (S, A)	3?	1	0	0	1?	0?	0?	0	0
Verification and Validation: S	S	4	3	4	3	1	2	2	4	2
Verification and Validation: M	M, A	2	1	1	0	1	1	1	1	1
Additive Manufacturing	M, A (S)	4	4?	4	2	0	2	1	0?	2
Multi-Material Add. Man.	M (S, A)	3	1	2	1	0	1	1	0?	2
Materials Separation	M	3?	1?	3?	1	0	3	3	1	1
Industrial Processing	M	1	1	1	0	0	1	1	0	1
Space Nuclear Power	M, S, A	2	1	4	0	0	0	0	0	0
Wireless Power Transfer	S, M (A)	0	0	2	0	0	1	0	0	0

Table Key:

0: The country has not indicated they pursuing development of this technology

1: The country has announced an intention to develop or has made some progress in this technology

2: The country is actively working towards developing this technology

3: The country has demonstrated this technology in order to develop an OSAM capability

4: The country has used this technology in an OSAM application

Table 4-2. Level of Country OSAM Capability by Country

OSAM Use Cases	US	CN	RU	JP	DE	UK	EU	CA	AU
R1: Remote Inspection	3	3	3	2	2	2	2	2	3
R1: Close Inspection	3	2	2	2	2	2	2	2	0
R2: Orbit Maintenance	3	2	2	2	2	2	2	2	0
R2: Orbit Transfer	3	2	2	2	2	2	2	2	0
R2: Deorbit	3	2	2	2	2	2	2	2	0
R3: Refuel	3	3		0	2	2	2	2	0
R4: Repair	2	1	1	1	2	1	2	2	0
R5: Replace Parts	2	1	1	1	2	1	2	2	0
R6: Power Beaming			2						
R6: Solar Reflection	1	1				1			0
R6: Direct Power	2	2	2	1	2		2	2	0
A: Basic	3	2	3	3	2	1	2	3	0
A: Precision	1	0	0	0	0	0	0	1	0
A: Platforms	2	1	2	1	2	1	2	2	0
M: Basic	3	2	3		0				1
M: Advanced	1		1		0				0
M: ISRU	1	1	1	1	1	1	1	0	1
M: Recycling	1				0				0

Table Key:

0: This country is missing more than one critical technology and will not likely be engaging in this activity soon

1: This country is not yet capable, but has some advancement in the main critical technologies and has invested in the application

2: This country has all of the technology prerequisites (or at least the most important ones) and could be capable within 5 years with minor effort

3: This country is already engaged in some form of this application

D. International Partnerships in OSAM

Partnerships, especially international ones, are an important indicator of the sector's maturity (as well as its ability to mature). In our research and interviews, we therefore aimed for a better understanding of the network of the OSAM sector, looked for where partnerships exist or are lacking, and identified which countries are actively involved or disconnected from the landscape. We identified partnerships between governments, private entities, academic institutions, venture capital firms, and angel investors. Figure 4-10 presents our findings graphically. Arrows indicate that the partnership is mostly one-way, such as through funding or technology transfer in one direction, rather than collaborative.

Three key multinational partnerships to highlight include:

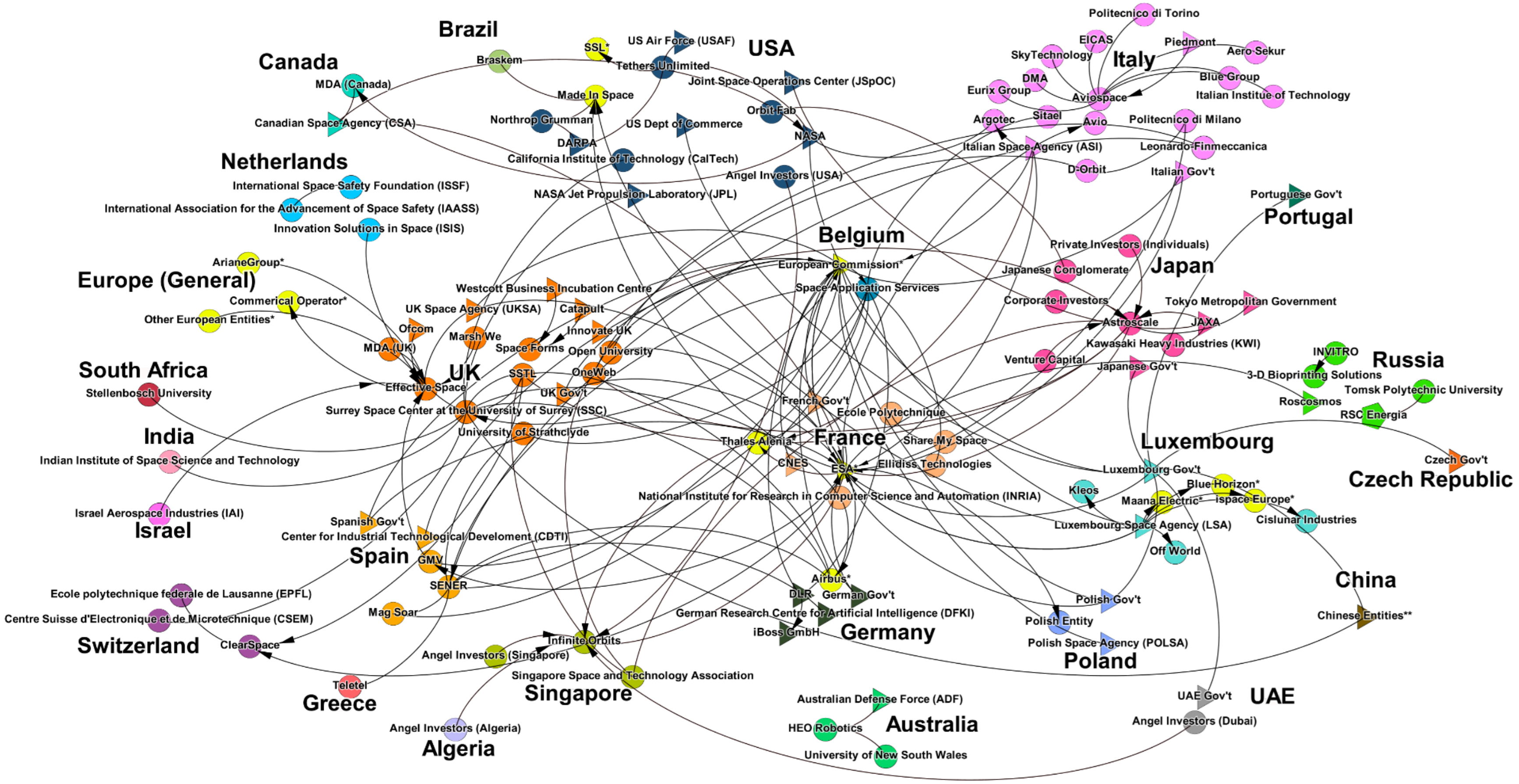
- The Consortium for Execution of Rendezvous and Servicing Operations (CONFERS), a consortium of private entities and academic institutions from across the world that aims to develop best practices and standards for the government and industry to follow and establish with regard to on-orbit satellite servicing and RPO (CONFERS 2020)
- PERASPERA, a partnership between seven European space agencies (ASI, CDTI, CNES, DLR, ESA, PSA, and UKSA) working to deliver key enabling technologies and demonstrate "autonomous robotic systems" needed for on-orbit satellite servicing and planetary exploration (Horizon 2020)
- Space Safety Coalition (SSC), an industry-led group comprised of space operators, space industry associations and space industry stakeholders, established to develop and maintain a set of "living space-safety best practices."

The network diagram demonstrates the interconnectedness of the international landscape and where partnerships have formed thus far. In Section A of this chapter, we noted that more than 100 entities in 26 countries are actively engaged in OSAM, including the United States, the United Kingdom, Belgium, France, Luxembourg, Italy, Germany, Spain, Japan, China, and Russia. Across these entities, we identified over 150 partnerships. A qualitative analysis of these partnerships reveals the following characteristics:

- The majority of countries engaged in OSAM have a partnership with at least one other entity located in a different country either as a customer, a servicer, a funder, or a user of a service; have an established MOU; or have a technical agreement.
- The United States, the United Kingdom, France, Germany, Belgium, Italy, Luxembourg, Spain, and Japan make up the hub of OSAM activities based on the number of entities in those countries and their number of international partnerships.

- Many countries on the fringe of the OSAM landscape, such as Algeria, Greece, India, and Israel participate in the OSAM landscape by means of their academic institutions, angel investors, or federal governments.
- Most of the countries at the center of the OSAM partnerships landscape are European, signifying that European OSAM entities have the most international partnerships in addition to being the most interdependent. This comes as little surprise given that all but one European country that belong to the hub of the OSAM landscape are members of the European Union, and do not seek funding or carry out space activities in isolation from their EU counterparts. A prime example of the interdependency of European OSAM entities includes the 18 Italian OSAM entities we identified, all of which are entirely dependent upon their connections with European entities and NASA.
- The United States is well integrated in the OSAM landscape internationally and plays an important role in OSAM activities, but is less central to the landscape than the European Union. Most likely, the United States is able to be less involved internationally because it is less dependent upon other countries to develop key technologies, policies, and raise funds.
- China and Russia are not as integrated in the international OSAM partnership landscape, but both have partnered with crucial players. The only international partnerships China has that we identified is its relationship with the Luxembourg government and the University of Surrey, signifying that while it is connected to two important international players, it intends to progress independently. Similarly, the only partnership Russia has that we identified is its relationship with ESA, another crucial player in the OSAM landscape.

It is important to note that our findings are not a reflection of every OSAM partnership in the greater OSAM landscape, and partnerships are constantly being created (or dissolved) in this fast-changing sector. It is also worth mentioning that a country with fewer OSAM entities engaged internationally does not mean that country is unimportant in the OSAM network.



○ - Non-government entity △ - Government entity ⬠ - Semi-government entity **Yellow shape with *** - Multinational entity

Notes: Not all U.S. entities engaged in OSAM are included given that this graphic aims to visualize non-U.S. partnerships. Additionally, the partnerships between CONFERS and PERASPERA members are not included.

** - See the China case study in Appendix C for more details on entities and domestic activities in China

Figure 4-10. Network Map of International (Non-U.S./U.S.) OSAM Partnerships

E. Policy, Legal, and Regulatory Activities in OSAM-Related Areas

In our research and interviews we found that in all countries of interest, OSAM regulation is absent or at a nascent stage. In some countries with private sector entities, we found supervisory measures meant to oversee the legal operation and execution of in-orbit activities, such as licensing, interagency review processes, and requirements for insurance (Foust 2018; Johnson 2014). Other countries have restrictions and standards with respect to advanced systems and technologies needed to properly and safely conduct OSAM activities, including technical specifications and import and export laws on intellectual property. Lastly, we noted national or international frameworks that supervise interactions between entities engaging in OSAM. This can include international and national regulatory bodies that regulate space activities and policies that establish codes of conduct and determine responsibility between disagreeing parties, especially with regard to disputes concerning liability, risk, control of space objects, and ownership.

The lack of legislation solely dedicated to OSAM poses an issue for entities interested in participating in the growing market. As it stands, most parties rely upon longstanding international agreements including the Outer Space Treaty of 1967, the Space Liability Convention of 1972, and guidelines developed by the Committee on the Peaceful Uses of Outer Space (COPUOS), but most existing international agreements provide “little clarity on the mechanisms to govern these activities” (Wheeler 2018). OSAM activities depend on interactions between private and state actors, yet there are only general provisions in place rather than established international best practices that can guide activities today.

According to some of our interviewees, national governments have generally not established specific policies or regulations regarding on-orbit servicing, assembly, or manufacturing due in part because OSAM has not been considered as high of a political priority as other space activities such as launch or Moon exploration. Appendix D provides a country-by-country overview of current policy regulations and observations made by interviewees regarding OSAM policy.

1. Status of Policy Regimes

Currently, there is little detailed legislation at the national level that directly guides or regulates OSAM. In national science and technology strategy documents, many national governments have acknowledged the responsibility and role they have in developing best practices regarding space activities, which includes supporting the international community as it conceptualizes and instates international regulations relevant to OSAM activities. This is especially true for ADR, where most of the countries we examined have written language recognizing the need to address the growing problem of in-orbit debris, especially as more countries and private entities develop and launch satellites. Some countries have developed debris mitigation guidelines as a result, or have outlined the development of guidelines as a goal in the near future.

Current science and technology statements that mention OSAM or OSAM-relevant activities are helpful in understanding where states prioritize OSAM in comparison to other space activities, how states anticipate OSAM supporting other facets of their politics (e.g., economic development, remaining technologically competitive), and how OSAM aligns with national science and technology goals. Statements made thus far also serve as catalysts for guidelines countries have created, such as debris mitigation guidelines and licensing procedures. However, many interviewees with whom we spoke emphasized that clearer guidelines and policies are needed for OSAM to grow. For example, without policy that obligates OSAM entities to remove debris, the business case for ADR is unlikely to close.

Luxembourg is one of two nations globally (together with the United States) that has a regulatory framework that guarantees property rights in space. As such, companies that are seeking to develop in-space manufacturing and ISRU capabilities have been attracted to the country as a base for their activities. While these companies still have much work to do before achieving the technical sophistication needed for a commercially viable in-space manufacturing business, the existence of Luxembourg’s regulatory framework for in-space resource extraction and manufacturing has drawn more companies and more financial investment than any country outside of the United States.

Table 4-3. High Level Assessment of Policies, Legal, and Regulatory Activities Related to OSAM

Country	Presence of Policy, Regulations or Guidelines for OSAM (e.g., OSAM legislation, standards)	Plans to Develop OSAM Relevant Policy, Regulations or Guidelines (e.g., strategic documents)	Country Participation in OSAM Related Global Fora (e.g., CONFERS, PERASPERA)
USA	🟨	🟩	🟩
UK	🟨	🟩	🟩
Canada	🟨	🟩	🟩
Australia	🟥	🟩	?
New Zealand	🟥	🟥	?
Germany	🟨	🟩	🟩
France	?	🟨	🟩
Italy	🟨	🟩	🟩
Luxembourg	🟨	🟩	🟩
Europe/ESA	🟨	🟩	🟩
Japan	🟨	🟩	🟩
Singapore	🟥	🟥	🟥
China	?	🟩	🟥
Russia	🟥	🟥	🟥

Note: Question mark indicates no information for the country

Key: 🟥 No Progress 🟨 Some Progress 🟩 Significant progress

2. Overall Trends

We observed two broad policy and regulation related trends in the OSAM sector. First, the interest in OSAM is both bottom-up and top-down. Some space agencies are working towards developing business environments where the private sector can grow and promote the progression of OSAM with collaboration with the government (e.g., Luxembourg, the United Kingdom, and the United States). OSAM-related activities in other countries are largely or entirely government-driven (e.g., China, Russia). Three sub-trends stand out in particular:

- Some non-government entities are looking to the government to help facilitate the progression of OSAM outside of technology development. Some OSAM entities/startups we interviewed stated they needed further government support with regard to funding for the industry and support for intellectual property.
- Interviewees emphasized that the challenge with OSAM has less to do with the development of technology and more to do with the business case and capital

formation. The lack of regulation requiring satellites to be deorbited could be seen as an inhibitor of growth on the commercial side.

- The concept of a "one-stop-shop," a streamlined way of processing applications, licensing, and regulating commercial activities, has been described as an ideal way to conduct operations but has not been established in countries more advanced in OSAM (such as the United States and the United Kingdom). However, New Zealand has a one-stop-shop in place, a process that could attract companies.

Second, we note that country-level policy in OSAM is uncoordinated internationally. Currently, OSAM policies are developed country-by-country and controlled by space agencies or regulatory bodies. Some interviewees with whom we spoke believed it was unlikely a common international OSAM policy would be established in the next 10 to 15 years, while others believed the international community could make progress with developing bottom-up standards. In particular, most interviewees noted that a major collision could serve as an impetus for OSAM policy within countries or internationally. Given a significant collision has not occurred in LEO or GEO, the lack of a major event could explain the lack of urgency over an OSAM policy. However, there is a push towards the establishment of standards, and multinational groups such as CONFERS and the Space Safety Coalition are leading the way on the conversation of regulations and standards.

3. Policy Barriers

Interviewees noted a range of barriers with respect to implementing their OSAM related plans:

- Uncertainty: There is still uncertainty over how servicers would be licensed, what restrictions exist over OSAM activities, and how those restrictions would affect relevant parties' business plans.
- Lack of Process: The lack of an affirmative policy statement or clear licensing pathway has created a sense of uncertainty and is a barrier to OSAM's growth. Currently, entities that want to participate in on-orbit servicing have governments that say "come talk to us" and address their needs on a case-by-case basis; many entities we interviewed mentioned that a "one-stop shop" with clear guidelines would further their ability to engage in OSAM.
- Market Interest: No player in OSAM has made a profit from commercial on-orbit servicing yet. There are many interested in on-orbit servicing, but few if any are willing to pay at this moment; entities' reluctance to finance on-orbit servicing efforts provides the government an opportunity to play a larger role and prove the concept.

- Restrictions on non-Earth imaging: Uncertainty is an issue, but even private entities that have received licensing in the United States are concerned about restrictions on non-Earth imaging, which may limit what on-orbit servicing activities they can participate in over the long term. This will become a greater issue for the growth of other commercial on-orbit servicing activities such as inspection and anomaly resolution.
- Politics: Though there are national space policies/directives/agencies in place, domestic policies in some countries (such as OSAM not being a high enough priority in the United States, Germany, and other countries) prevents progress on implementation.

F. Summary

STPI identified 17 countries/regions with OSAM related activities. However, fewer than 10 countries have activities worth watching. Table 4-4 summarizes the key features of OSAM in these countries. Detailed case studies are included in Appendix C.

Table 4-4. Key OSAM Information for Select Countries of Interest

Country	OSAM Areas of Interest	Key Government Institutions	Key Companies	Funding (if known)	Key Funders	Key Partnerships
United Kingdom	S, A, M	UKSA	Effective Space, SSTL	UKSA provided €23.3 million to OneWeb. Other funding unknown	UKSA	UKSA and Roscosmos; Effective Space and UKSA; SSTL and Astroscale
Canada	S, A	CSA	Maxar/SSL	CSA's annual budget is CA$285 million. OSAM-specific funding is unknown	CSA	CSA and Maxar; CSA and NASA
Australia	S, O	ASA	HEO Robotics, Exodus Space Systems	ASA's annual budget is AU$40 million. OSAM-specific funding is unknown	ASA	Australian Defense Force and HEO Robotics
New Zealand	O	NZSA	Rocketlab	NZ$3 million for early stage R&D, unknown if OSAM-related yet	NZSA	NZSA and DLR
Germany	S, A	DLR	iBOSS GmbH	DLR's 2019 budget is about €300 million. OSAM-specific funding is unknown	DLR	DLR and iBOSS; DLR and European Commission through PERASPERA
France	S, A	CNES	Thales Alenia	Funding unknown	CNES	CNES is a member of PERASPERA; Thales Alenia and ESA
Italy	S	ASI	Argotec	Funding unknown	ASI	Argotec and NASA; ASI and Roscosmos
Luxembourg	M	LSA	OffWorld, Maana Electric, Blue Horizon	Largely unknown. Some companies have disclosed sub-million Euro investments	LSA	LSA and ESA
Europe/ESA	S, A, M, O	European Commission, ESA	ClearSpace (Switzerland), Airbus (the Netherlands), AVS (Spain)	ESA and the European Commission each spent around €10 million on OSAM in 2019	ESA, European Commission	ESA and Roscosmos; European Commission and DLR, ASI, UKSA, and more through the PERASPERA consortium

Country	OSAM Areas of Interest	Key Government Institutions	Key Companies	Funding (if known)	Key Funders	Key Partnerships
Japan	S, A	JAXA	Astroscale	Approximately $940 million to support space R&D and space startups; Astroscale has raised $140 million to date.	JAXA, Corporate Investors, Venture Capital, Private Investors, Tokyo Metropolitan Government	JAXA and Astroscale; Astroscale and JSpOC
Singapore	n/a	Singapore Space and Technology Association	Infinite Orbits	More than $250,000	ESA, Angel Investors	Singapore Space and Technology Association and European Commission; Infinite Orbits and ESA
China	S, A, M	CASC, CASIC	i-Space	Funding unknown	Chinese government	Chinese government and CASC/CASIC; Chinese government and Luxembourg Space Agency
Russia	S, M	Roscosmos	RSC Energia, 3-D Bioprinting Solutions	Funding unknown	Roscosmos, INVITRO	Roscosmos and RSC Energia; 3-D Bioprinting Solutions and INVITRO

Note: See Appendix C for more details on the individual countries.

5. Drivers of OSAM

A major goal of this study is to identify and predict, to the extent feasible, global trends in OSAM over the next 10 to 15 years. Where OSAM is in a decade or more from now depends on a variety of factors that could potentially accelerate or inhibit the development of OSAM technologies and market cases. In anticipation of making our forecasts for the next decade, in this chapter, we discuss factors that may affect the future development of OSAM.

Some of these factors also have second- and third-order impacts on OSAM's future with regard to their interconnectivity with other factors. We will first discuss the full set of factors we believe may influence OSAM's future, focusing on how changes in the occurrence or prevalence of these factors could alter the development of OSAM (and the ways and directions they affect OSAM). We will then discuss the potential interactions among these factors that illustrate the inherent complexity in attempting to predict the future of OSAM activities. We will conclude by identifying a subset of factors that we believe may be the most influential in shaping the development and adoption of OSAM technologies in space over the next 10 to 15 years. This subset represents our estimation of the most important factors to track when evaluating the future direction of OSAM activities.

A. Drivers of OSAM Related Capabilities

Drivers that may influence the development and adoption of OSAM capabilities can broadly be split into six categories: technology drivers; government market drivers; commercial market drivers; infrastructure and architecture drivers; policy drivers; and discrete event drivers. Accounting for drivers from all these categories is vital to understanding the direction of the OSAM ecosystem: technology developments are critical for making OSAM scientifically feasible; a market case for using OSAM capabilities must exist in order for them to proliferate; policy and regulatory frameworks can both encourage and discourage the use of OSAM technologies; and discrete events and other wild card factors can invigorate or deflate interest in OSAM. This initial listing in Section A provides those drivers that directly impact the development of OSAM. We discuss how these drivers influence one another to have higher-order impacts on OSAM in section B. Lastly, in Section C we list what we believe to be the key drivers and those to which OSAM developments are most sensitive. In all cases, we mark whether the impact is positive or negative in parentheses.

1. Technology Drivers

a. OSAM-Specific Technologies

Chapter 2 of this report itemized 23 technologies relevant to the development of OSAM capabilities, flagging those that were critical versus desirable or enhancing. Three broader areas in particular are important drivers of OSAM:

- **Software (+):** Automation, computer vision, and other software are required to conduct autonomous operations in space. Computer vision is particularly important for non-cooperative servicing and RPO, while removing humans from the loop by using tools such as machine learning would make OSAM operations more secure in the event of a cyberattack or loss of signal at the moment of approach, since robotic elements would still ensure mission integrity. Many of these capabilities have been developed for other applications on Earth; efforts to spin-in these technologies could advance them faster than if they were developed independently.
- **Mechanisms (+):** Robotic arms, mechanical interfaces, fiducials or markings on a spacecraft, grapplers, modularity in client payloads, camera systems, and many other technologies are needed for many OSAM operations. Increasing the reliability, lifetime, efficiency, and standardization of these hardware elements will help accelerate the development of many of the OSAM capabilities discussed in the previous chapters. Like the software that would control these mechanisms, most of this technology exists in other sectors and could be rapidly spun-in, though there are sufficient differences between mechanisms operating in space and mechanisms operating on Earth that this would not be an easy transfer.
- **Guidance, Navigation, and Control (GNC) (+):** GNC is a prerequisite backbone for any system conducting OSAM, since the servicer will need to conduct RPO with the client vehicle. Increasing the precision and decreasing the mass and cost of such systems would drive OSAM activities. Unlike software and mechanisms, GNC cannot be spun in from other sectors, but it could be proliferated quickly from inside the space sector given how many entities already have GNC capabilities fit for OSAM.

b. Other Technologies

Other technologies developed for activities other than OSAM can greatly expedite OSAM activities. These include:

- **Electric Propulsion (+/-):** Electric propulsion systems could help vehicles conducting OSAM operations last longer and service more clients because maneuvering would be both more precise and more efficient. However, reliable electric propulsion would also decrease the market for refueling services if potential client satellites shifted to using electric propulsion instead of fluid fuel sources.

- **High-Power Systems (+):** Maturation of systems that can provide much higher power density than photovoltaic systems would enable larger scale manufacturing and highly efficient relocation services. An abundance of power could enable platforms to conduct more research in industrial applications in manufacturing or ISRU, and would be particularly beneficial for studies of space debris recycling. In addition, nuclear propulsion can be used for relocation services, especially between LEO and GEO; electric propulsion may take 6 months to a year, but nuclear may just take days.
- **Deployable Systems (+/-):** Proliferation of advanced deployable technologies would decrease the need for on-orbit assembly, but would increase the need for remote inspection and repair services to validate and correct deployables.
- **Optical Communication (+/-):** Also known as laser communication or lasercomm, this form of data transmission uses higher frequencies than radio, typically infrared light, to transmit signals. Lasercomm has many advantages, such as higher data throughput, better security, and lower power requirements, but also many disadvantages, such as the need for higher pointing accuracy, fewer ground stations, and more variability in ground station availability due to clouds. Although it does not directly drive OSAM activities, it can drive satellite design choices, mission operations, and other aspects of the OSAM market.

2. Government Market Drivers

In order for most commercial entities to justify committing funds and effort into developing OSAM capabilities, there must be a market case for using the service once produced. Many potential service providers have indicated that a large government mission pull will be necessary to inject funds to get OSAM off the ground. Examples of mission pulls include:

- **Lunar Programs (e.g., Gateway, Artemis, Moon Village) (+):** Government investment in lunar programs could have tremendous pull on many OSAM-related technologies. Assembly is key for the Lunar Gateway, as are standards for its interfaces and robotic arms. The Gateway may also need refueling services over its lifetime. As lunar programs evolve from the initial landing mission, cargo delivery from relocation services such as logistics providers will be key to maintaining lunar presence. Government missions often do not abide by rules that require profit making as private ventures do. Lunar programs in particular could generate the business case for OSAM service providers, especially in the domain of assembly operations.

- **Mars Mission Pull (-):** Unlike lunar programs, Mars missions will likely create little demand for OSAM, because currently proposed missions focus less on creating a sustainable platform or on developing ISRU, and more on basic science or human missions. In fact, because of the different technological requirements for a Mars mission and the desire for more integrated and monolithic architectures, countries that are focused on Mars instead of the Moon likely will experience a decreased rate of development in OSAM.
- **Earth Observation (+):** The current regime of Earth observations systems does not require OSAM services. However, if there were a shift to using a constellation of satellites in LEO for Earth observation, then relocation and refueling services could become necessary. Alternatively, if a persistent platform is developed as the new norm of observation systems, then replacing parts and general assembly capabilities would prove vital. Such a scenario would create the mission pull for many OSAM technologies.
- **Deep Space Observatories (+):** The next large space telescope after the James Webb Space Telescope will be unable to fit inside a standard rocket fairing if it is to provide substantial improvements in its capabilities. In-space assembly is the only economical way to construct such a telescope for future space physics missions. If a government were to commit to such a telescope, it would rapidly accelerate the maturation of on-orbit assembly (which would also benefit servicing-relevant technologies).
- **Increased Militarization of Space (+/-):** Increased probability of conflict in space may create a large demand for OSAM services in the government sector as part of its plan for greater resiliency and redundancy in space. Refueling could enable rapid repositioning of military satellites; repairing and replacing key components on a satellite would provide defensive capabilities for space objects, and the large amount of debris created by any attack on a satellite would necessitate debris removal. On the other hand, increased militarization can reduce overall commercial investment in space due to the uncertainty and risks of conflict in space.

3. Commercial Market Drivers

A government market pull is a strong driver of OSAM. However, there could be a similar demand from households and businesses as well. Examples of mission pull from non-government customers include:

- **Demand for Communications Services (+):** Some experts have noted that growth in the demand for broadband and other communications services (though not satellite TV or other non-internet services) will likely have an effect on OSAM. As we noted in Chapter 2, the demand for broadband internet services is growing globally and space-based delivery of internet would be challenged to improve. In addition to this demand, which fuels interest in large LEO constellations, other trends create opportunities for space-based communications. These include the development of the new 5G communications standard, which will require much greater bandwidth globally; the related development of the Internet of Things; and the advent of drones and self-driving cars.
  - If LEO-based broadband services are successful, OSAM services may be called upon to remove nonfunctioning satellites or to tow satellites from incorrect to correct orbits.
  - If GEO-based satellites become a bigger part of broadband provision, other OSAM services (repair, replace parts, assembly) may see more considerations. In this case, OSAM may be called on to add new components to satellites more cheaply and frequently than by launching entire new satellites; to assemble large antennas that support higher data rates over more beams; and to refuel, reposition, or dispose of satellites for constellation management.

  However, if terrestrial services vastly outperform space services through advantageous lifecycle properties like rapid deployment and iteration, even with the growth in overall demand, space communication could fail to maintain its market share, and all OSAM services could see lower likelihood of commercial success.
- **Investor Confidence and Availability of Venture Capital (+):** Venture capital is essential for advancing technologies outside of government drivers and for expanding the commercial market for OSAM-related services, but investors are less likely to provide capital to the industry if the risk of failing appears too high. A failure in one area of the commercial space domain makes it difficult to raise capital in another, even if the two are unrelated technologically or in market capture. Areas with higher perceived risk, like OSAM, are at a higher risk of rapidly shifting investor confidence levels, which could create disruptions that could interrupt R&D roadmaps and pipelines.
- **Value Proposition Methods (+):** In addition to investor confidence, another issue is whether there is a tangible and significant return on investment. The tangible, upfront costs of designing a satellite to be serviceable are typically

justified by intangible, uncertain benefits that are dependent on off-nominal mission outcomes. It is therefore difficult to compare these added costs with business-oriented value-centric design methodologies. This return is not as dependent on upfront investment as is commonly believed. Other domains invest in activities that are capital-intensive. For example, upfront costs of offshore rigs and semiconductor manufacturing plants are both in the many billions of dollars, and the capital typically comes from capital markets (EIA 2016; TSMC 2017). Private capital markets can do this because the returns on these investments are well assured. If the value proposition of OSAM can be better articulated (see Chapter 3), both internally (i.e., understanding how the services affect their bottom line and profits) and externally (i.e., how OSAM can increase value for customers), companies can better balance the choices and needs of OSAM and more easily consider them as part of their design space. This, combined with capabilities such as on-demand (responsive) launch and proliferated space infrastructure, will better communicate the true market or strategic case for making decisions in OSAM. Methods used to do so must balance expressing the benefits of flexibility in design with the cost and effort required to design for it.

4. Launch and Infrastructure Drivers

Launch is an important driver of OSAM activities, as is the cost and availability of other infrastructure:

- **Cost of Launch (+/-):** Lower launch prices could accelerate OSAM technology development, as it would become more affordable to flight-test new systems. Higher launch costs would stifle the development of OSAM-focused startups, since it would become prohibitively expensive to demonstrate their services in space, effectively making it impossible to prove the market case. However, cost of launch can also weaken the case for OSAM, as discussed in section B of this chapter.
- **Responsiveness of Launch (+):** If launch were to become readily accessible, such that the time between scheduling a launch and the actual launch date was substantially decreased from the current timeframe, satellite operators could respond to unexpected satellite failures or incorrect orbital placement during launch by purchasing satellite servicing to repair or relocate the satellite. The servicer would be able to rapidly launch, minimizing the downtime of the operator’s product.
- **Availability of Launch (+):** Separate from the timeliness of launch, if there is an increase in the availability of launch, servicers would have more opportunities to launch nascent technologies to prove their spaceflight readiness.

Such technologies could include OSAM capabilities themselves, but also mission payloads that could later by installed by OSAM. In addition, increased availability of rideshare services and small launch vehicles would make frequent launches of components more accessible to OSAM companies in particular, which complements larger systems using all or a majority of the payload space on a launch vehicle.

- **Availability of low-cost, precise, and accurate SSA services (+):** SSA can provide independent verification of an OSAM operation, which would bolster customer and global confidence in OSAM activities. In addition, SSA directly enables debris tracking, which is a critical supporting technology to facilitate debris removal.
- **Ground Stations (+):** More ground stations spread across Earth would support SSA and debris tracking, which would facilitate rendezvous operations critical for all OSAM services.
- **Cybersecurity (+):** Enhanced cybersecurity measures would promote confidence in OSAM activities. Conversely, lack of cybersecurity could jeopardize the success of OSAM missions, as cyberattacks could interfere, particularly during non-autonomous operations.

5. Policy and Regulatory Drivers

Government policies and regulations have the potential to alter the future of OSAM, as they could either require OSAM services be obtained by satellite operators or restrict the adoption of OSAM technologies. This section discusses potential policy and regulatory changes that would affect the development of OSAM, especially in the commercial sector.

- **End-of-Life and Debris Removal Regulations (+/-):** Regulations that require the rapid removal of satellites that are no longer operational would force satellite operators into acquiring deorbiting services, thus establishing a short-term market case for relocation. However, regulations could lead to satellite operators developing new technologies and attempting to avoid the need to purchase deorbiting services over longer terms and cause other effects that could negatively impact other OSAM services and activities.
- **Standards Development (+):** Open standards would help prevent proprietary systems from gaining too much market share or pushing out other entities, potentially leading to broader adoption of better OSAM technologies and applications.
- **Dual-Use Restrictions (-):** More technology sharing restrictions can prevent technology transfer, especially government-to-private transfer. Restrictions on

the use and export cases of specific technologies would also hamper the development of OSAM services.

- **Clarity on Property Rights in Space (+):** Regulatory regimes that establish an entity's lawful claim to resources in space would ensure the market case for salvage of objects in space, ISRU, and manufacturing. The lack of clarity on this topic is a substantial barrier for interested companies investing in the area.
- **Space Traffic Management or STM (+):** Legally-required STM (for example, mandates on maneuvering in case of high probability conjunction events) could necessitate satellite operators expending more fuel, which would potentially provide the market case for refueling services. A strong STM regime would also make OSAM activities safer and increase investor confidence in ventures that conduct RPO.
- **Architectures Using In-Space Infrastructure (+):** Instead of building large and powerful rockets, one could build smaller rockets that refuel in space. Such a disaggregated architecture that could support OSAM operations, such as fuel depots or parts storage facilities, would lower the barrier to entry of new OSAM companies, and would reduce the cost of providing services.
- **Policies Supporting Technology Transfer (+):** Policies that reduce the barriers related to the transfer of technologies from government to the private sector would greatly aid the technical development of OSAM. Reducing the timeline of technology development and acquisition for private companies would rapidly increase the rate of adoption of OSAM services.
- **Global Cooperation (+):** If governments explicitly adopted a policy of international cooperation in OSAM (e.g., development of norms of behavior related to RPO), it could lead to more common technologies, interfaces, and standards, as well as an increase in programmatic and investor confidence.

6. Discrete Event Drivers

A number of discrete events have the potential to substantially change the future landscape of OSAM.

- **OSAM Mission Success (+):** Successful missions (such as the recent recommissioning of an Intelsat satellite using R2) will increase investor confidence in OSAM, thus establishing a clear path forward to legitimacy for future OSAM operations. There is currently a reluctance to purchase OSAM services due to perceived risk, which a successful operation may reduce substantially.

- **Major Collision in Space (+/-):** A major collision in space, or to a lesser extent a series of near misses, could lead to a cascade of regulatory and operational changes. In particular, debris produced by a major collision may result in calls for debris regulations and removal operations, creating the business case for relocation services. Additional regulations or services, such as stricter STM, better SSA, and stricter end-of-life (EOL) regulations, would likely result, which could further support OSAM activities. A collision in space that degrades the space environment could also have a chilling effect on private investment in space companies.
- **Military Conflict in Space (+/-):** A military conflict could create a large demand of for OSAM services in the government sector. On the other hand, a conflict can also reduce overall commercial investment.
- **Cyberattack (-):** A cyberattack during an OSAM operation could decrease the adoption rate of OSAM services due to perceived vulnerabilities during highly sensitive RPO.
- **ISS Deconstruction (+/-):** If the ISS is deconstructed, the development rate of OSAM technologies, especially in countries that use the platform, would likely decrease. The ISS is currently a testbed for many technologies that play a key role in OSAM, including autonomous docking, robotic arms, standardized interfaces, and modular systems. Deconstructing the ISS would eliminate a key platform for developing those technologies. However, a potential replacement to the ISS could be predicated on principles of modular architectures and autonomous activities in space, for which OSAM technologies would play a key role.
- **“Wildcards” (-):** Other discrete events that are difficult to predict are likely to have impacts on OSAM. These events may not be at all related to OSAM or even space, but could affect drivers discussed above. For example, Brexit could have impacts on space partnerships between the United Kingdom and Europe and disrupt some space component supply chains, and the uncertainty can decrease investor confidence and slow technological development because of other priorities (Feldscher 2019). A satellite operating on an unlicensed frequency or conducting other criminal activity could lead to additional regulations and inspections (Henry 2018). A global disaster such as the COVID-19 pandemic has the potential to disrupt talent pools, supply chains, and access to capital (OneWeb 2020).

B. Interconnectivity Among Drivers

Each driver discussed above may have an influence on one or more OSAM elements, but each driver can also influence other drivers, creating competing forces that make it difficult to predict the directions that the sum of all drivers will influence OSAM developments. Some drivers can have a positive effect on one area of OSAM but a negative effect on another. As a result of the complexity of how these factors interact with one another, there are many feedback loops or time-delayed effects that are created. These loops mean that single factors can indirectly accelerate or inhibit an OSAM area by themselves, or could have a direct positive effect, but an indirect negative effect on an area of OSAM.

Figure 5-1 illustrates the interconnectivity among drivers, using only a small subset of key drivers to show the types of relationships that can be analyzed using this method. To examine higher-order effects of a driver on OSAM, readers can track the arrows from a single driver to an OSAM category through other drivers.

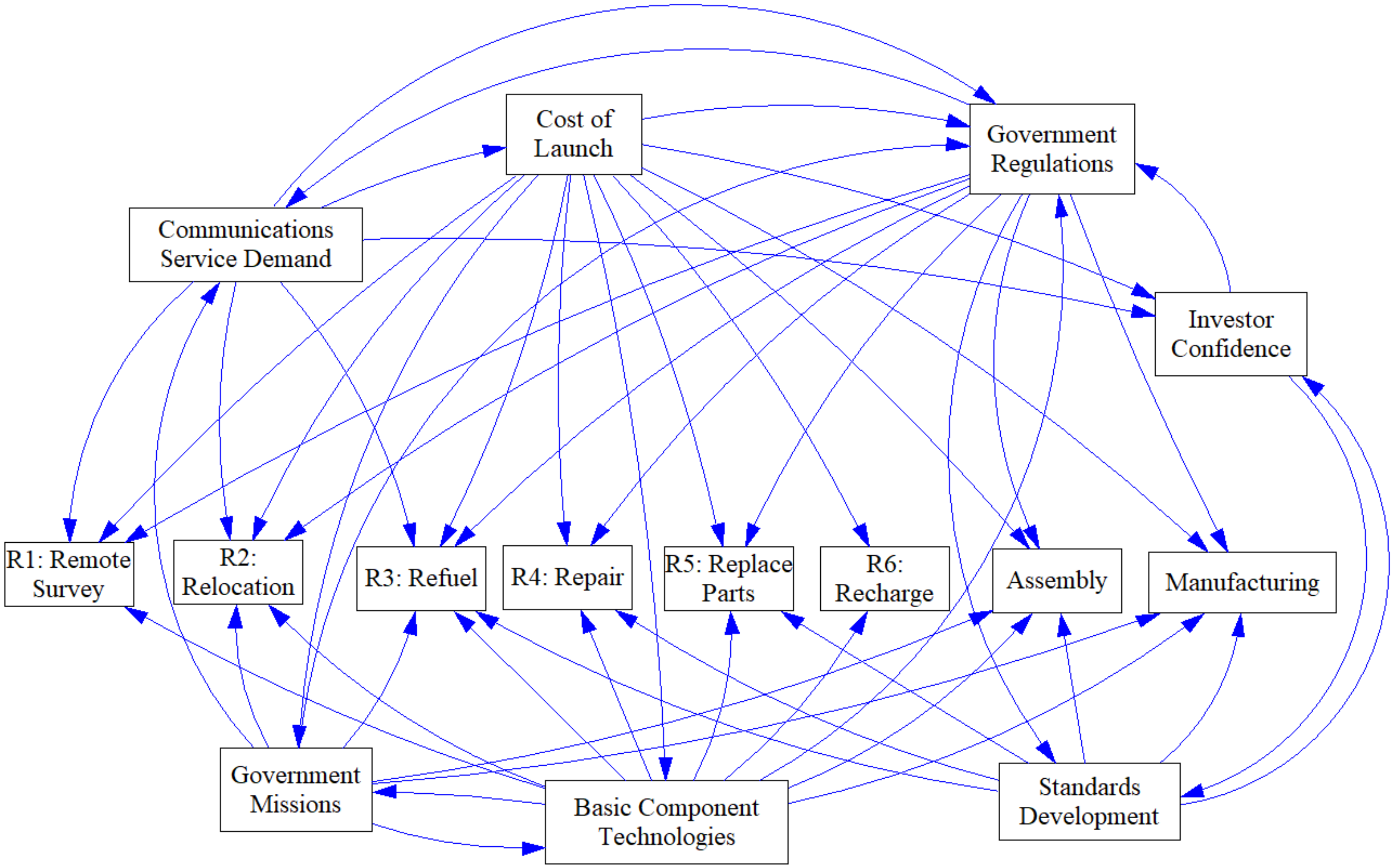
For example, reducing the cost of launch directly competes with refueling services (R3). The arrow from “Cost of Launch” to “R3 Refuel” indicates that there is a relationship between the two. In this case, the arrow indicates that a lower cost of launch would result in less demand for refueling services since it may be more cost effective to relaunch a new satellite rather than purchasing refueling services. At the same time, reducing the cost of launch would accelerate and facilitate government missions such as Artemis (as indicated by the arrow from “Cost of Launch” to “Government Missions”). Government missions will likely invest in and develop the basic technologies needed for OSAM (“Government Missions” → “Basic Component Technology”) because they will require standard interfaces between satellites and may directly involve refueling to enable repeated missions to and from Gateway and the lunar surface. Maturation of those basic technologies needed for refueling would support the development of refueling as a service as well. In this scenario, lower cost of launch directly inhibits the development of refueling services, but supports the technological development of refueling through the effects launch costs have on other drivers.

This example demonstrates the utility of the Deep Space Transport in elucidating how a single driver could have both a positive and negative effect on OSAM, depending on its effects on other drivers and on the amount of time elapsed. Below we discuss a few noteworthy examples of more complicated relationships between drivers that we discovered through our analysis of interactions between drivers. This list is not intended to be comprehensive, but instead to demonstrate how complex interactions between factors can lead to varying outcomes for OSAM.

- **Launch costs (+/-):** Launch costs affect nearly everything in the space industry. Lower launch prices can lead to a faster pace of technology development as it becomes more affordable to test new systems. However, a low launch price may also hurt the demand for some OSAM areas, since it may be cheaper to simply launch a new satellite rather than repair or replace it. Alternatively, high costs for launching large objects may in fact strengthen the value proposition of OSAM—it may be cheaper to assemble objects in space rather than to launch them. In addition, large launch vehicles can provide different services than small launch vehicles, so the pricing and availability for each type can affect different aspects of the space ecosystem. Small launchers are good for dedicated flights to LEO, and they can test critical technologies quickly. Larger launch vehicles are the only feasible way to get to GEO, no matter what size the payload is.

- **Availability of Launch (+/-):** The capability for on-demand launch can add a strategic element to the decision of whether or when to launch or purchase OSAM services. It can make it easier to replace parts on a persistent platform, but it can also make it easier to replace systems entirely. Responsiveness could play a role in decisions regarding constellation management as well as battlespace positioning. Small launch vehicles are likely to be more responsive than large ones, which is good for technology development but most likely not for GEO operations.
- **Government missions (+/-):** A lunar mission pull such as the Gateway system would have compound effects on OSAM. During the course of mission preparation and execution, a number of key component technologies would need to be developed, which could in turn spur or depress the development of OSAM. For instance, ISRU, a subsection of the manufacturing area of OSAM, could be necessary to create a durable presence on the Moon. ISRU would likely require developing high power systems in space such as nuclear power to aid in the production of water and oxygen. The existence of nuclear power systems for use in space would likely make relocation services less necessary since the client could opt for nuclear-based propulsion instead. At the same time, a servicer that was capable of harnessing nuclear power would be able to maneuver faster and at lower cost, allowing it to provide repair or replacing parts services to many more clients than previously feasible.
- **Cyberattack (+/-):** A cyberattack during an OSAM mission could lead to increased militarization of space, more emphasis on cybersecurity in space systems, advances in software in OSAM systems, and a boost in secure laser communications. It could also affect investor confidence, other space agency priorities, and standards development. It could have both positive and negative effects on international cooperation, as countries either protect their assets against all other countries or attempt to cooperatively address the new threat.

- **Regulations (+/-):** Regulations on space debris could make relocation and deorbit services more attractive, but it could have a detrimental effect on the overall space market if fewer activities occur because of greater governmental restrictions. Alternatively, with stricter regulations, satellite operators would be less willing to risk needing to purchase deorbit services and would behave more responsibly to avoid paying for removal services.
- **Conflict in Space (+/-):** Increased militarization of space could lead to more OSAM activities for strategic applications, but it could also affect technology transfer regulations, making innovation outside of those capabilities more difficult and controlled. Technologies may mature faster, but commercial market and civil cases may evolve more slowly.



Note: Arrows indicate interconnectivity (e.g., Cost of Launch drives nearly all OSAM activities, and it is also driven by Communications Service Demand)

Figure 5-1. Visualization Demonstrating Interconnectivity Among Drivers

C. Key Drivers and OSAM Sensitivity

In our research, we identified more than 50 drivers of OSAM, but not all drivers are equally important. In addition to driving OSAM activities, they also drive each other, directly and indirectly. To better characterize these potentially competing relationships, STPI created a DSM to characterize how each driver influences OSAM development as well as how the drivers affect one another (Eppinger and Browing 2012). The methodology is included in Appendix F. The final matrix assigns a weight, sign, and direction to the relationships between each driver and every other driver, as well as between each driver and each OSAM area. By evaluating the number and strength of the connections between drivers, we were able to analyze: (a) which drivers had the strongest direct influence on OSAM; (b) which areas of OSAM were most sensitive to changes in conditions of the space ecosystem; (c) which drivers had the strongest second-order influence on OSAM with regard to their influence on other drivers; and (d) which drivers were the most sensitive to changes in other drivers.

Based on this assessment, we believe that the drivers that carried the most direct influence on OSAM were basic component technologies like advanced robotics and GNC systems, the cost of launch—particularly the cost of heavy launch, and the development of standards and regulations (Table F-2). OSAM activities cannot take place without the necessary component technologies, so it is unsurprising that these basic building blocks had the greatest direct influence on OSAM's future. The cost of heavy launch has a strong direct influence on OSAM, and specifically a greater influence than the cost of small launch, because larger client satellites are more likely for customers to financially justify when purchasing OSAM services. In addition, cheaper heavy launch would allow larger, increasingly capable servicer satellites to be launched at low cost. Finally, standards and regulations enable OSAM by establishing norms of operation. Standards ensure that servicing in particular is less risky and better understood by the community. Regulations would have a strong effect on OSAM; dual-use regulations would inhibit the commercial development of servicing capabilities, while debris removal and EOL regulations would provide the business case for relocation operators.

The assessment also revealed that the OSAM areas that are the most sensitive to changes in underlying drivers are refueling and relocation services (Table F-3). The future of these two areas uniquely and strongly depends on dual-use regulations, EOL and debris removal regulations, RPO sophistication, robotic interfacing, and the balance between the LEO and GEO markets. Because refueling and relocation are so dependent on all these different drivers, their future relevance could vary drastically. If dual-use regulations are weak, EOL and debris removal regulations are strong, and GEO remains the major market for satellite operators, relocation and refueling could be critical to the future space ecosystem. If dual-use regulations are strong, EOL and debris removal regulations are weak, and LEO becomes the major market for satellite operators, then refueling and relocation services would likely become a niche market at best.

The DSM analysis also suggests that the drivers with the greatest influence on other drivers, and therefore the strongest second-order effects on OSAM, are increased militarization of space and the LEO satellite market size (Table F-4). In the event of space militarization, maneuverability, offensive, and defensive capabilities would all become essential. This would facilitate the development of refueling and relocation services, but would likely result in a tightening of dual-use regulations, which are a key driver of OSAM, as discussed above. Militarizing space may also lead to a greater number of collisions and a substantial increase in the amount of orbital debris, which would therefore require debris removal services. The LEO market size strongly influences whether re-orbiting services are considered necessary by satellite operators. A shift from GEO to LEO may break the market case for OSAM by shifting the space paradigm towards single companies owning a large number of low-cost satellites. Companies operating many low-cost satellites would be unlikely to justify purchasing servicing capabilities from third parties for practically disposable assets. Alternatively, since they already operate such a large fleet, they could provide servicing to their own satellites with dedicated servicers launched with their primary operational satellites while incurring relatively low penalties for transferring orbits, depending on the constellation design.

Lastly, we found that the driver most sensitive to other drivers, and substantially more sensitive than any other driver, is investor confidence (Table F-5). Since every substantive change in the space economy affects investor confidence in space and OSAM capabilities, it is no surprise that it is the single most sensitive driver. However, under our model, investor confidence is not a particularly strong primary or secondary driver of OSAM. This reflects the fact that venture capital is only one way, alongside government missions and regulatory requirements, that could substantially buoy the market for OSAM. Summarizing these analyses, Table 5-1 lists the seven most critical drivers of OSAM.

Table 5-1. Key Drivers in the OSAM Ecosystem

Driver	Rationale
Advances in basic component technologies (+)	Influences all OSAM capabilities and use cases
Cost of launch, particularly the cost of heavy launch (+/-)	Complex effect—lower launch costs can help prove out OSAM technologies but also make it cheaper to launch replacement satellites rather than repair them
Development of standards (+)	Standards establish norms for operations, but also ensure OSAM is less risky and better understood
Government regulations (+/-)	Restrictions can make or break the case for OSAM—most affect refueling and relocation services

Driver	Rationale
Government missions/decisions on architectures (+/-)	Government is a reliable customer (if it chooses architectures that can benefit from OSAM) and can build investor confidence
Demand for communications services (+/-)	Growth in space-based communications, if in LEO, may increase the need for deorbit services. If in GEO, it may drive the case for other OSAM services (repair, replace parts, assembly). However, there will be a negative effect if terrestrial services vastly outperform space services.
Investor confidence/venture capital (+)	Driven by other drivers, and also a strong driver of all commercial OSAM activities and technologies

6. Trends and Long-Term Outlook in OSAM

In 2009, a Federal Aviation Administration (FAA) report forecasting the demand for launch noted a decline in the number of small satellites launched, and forecasted an average of two small satellite launches per year from 2010 forward (FAA 2009). A decade later, in 2019, globally almost 400 small satellites were launched (Bryce 2020), an under-prediction by two orders of magnitude. Similar errors in forecasting have been noted in other areas. McKinsey, in its 1980s prediction of the growth of cell phones by 2000, was off by two orders of magnitude (The Economist 1999). Acknowledging the risk of making predictions, we write this chapter with apposite humility, and base our long-term outlooks on our understanding of the state-of-art in OSAM (Chapter 2), potential uses (Chapter 3), current activity globally (Chapter 4), and strength and speed of the drivers (Chapter 5).

A. Overall Assessment of OSAM Activities

Given the great uncertainties involved in OSAM operations, the technological risks involved with such activities, the current configurations of satellites on orbit today, and the difficulty in articulating the long-term value proposition of some higher-order competencies, STPI believes that in the next 10 to 15 years, key OSAM operations will likely become more common, but we do not expect to see explosive growth similar to what was seen with the small satellite or small launch vehicle markets.

From the perspective of commercial users, the first generation of satellite servicing will be the most technologically difficult given that satellites today are not designed to be serviced; the next generation of satellites launched with servicing as an option will not require servicing for some time. The standards required to reduce the risk for satellite operators to accept servicing options will take years to develop, and even more time to incorporate into the designs of the next wave of commercial satellites.

However, military and civil applications of OSAM could grow faster depending on the nature of future operations in space. Military satellites are some of the most expensive pieces of hardware in space, and basic servicing could restore national assets to functional capability. The strategic flexibility offered by refueling could revolutionize military systems in ways that commercial systems would not find as attractive or necessary. Far-reaching human exploration campaigns will likely need a supply chain that is not solely reliant on launch from Earth, especially given the long transit times. Applications such as radio telescopes could drive demand for large, robotically assembled structures in space. Each element of OSAM will be driven by a different set of drivers and mature in different ways. Section B summarizes our assessment of the next 10–15 years by OSAM area, and Section C discusses our forecasts by country.

B. Assessment by OSAM Area

For each OSAM capability (R1–R6, A, M), we provide our assessment of what may happen in the next 10 to 15 years.

1. Future of R1: Remote Survey

Remote survey is the most mature area in OSAM, principally because it is an essential first step for all other on-orbit activities. Today, it is led primarily by the governments of the United States, Russia, and China for civil and national security reasons. Driven by financial reasons (e.g., insurance payouts), there is a growing number of emerging companies globally that expect to provide close and ultra-close services. We expect the number of commercial providers in remote survey to grow over the next 10 to 15 years.

In contrast, we do not see ultra-close inspection being a service that is provided without being in combination with other services. The operations are complex, and do not provide much tangible benefit if they are not supplemented with other reasons to dock with a spacecraft. In the next 10 to 15 years, we expect ultra-close inspection to remain a government-sponsored activity performed in conjunction with national security reasons.

2. Future of R2: Relocation

Current activity in relocation services is ongoing, and technical success of the MEV appears likely at the time of this writing. If the mission is successful, other large (e.g., Airbus, Thales Alenia) and small (e.g., Effective Space) entities around the world will likely act to provide GEO relocation services.

However, several experts we interviewed agreed that the window for a reliable GEO relocation services market may only be open for the next 8–10 years. The current generation of GEO communications satellites is near the end of its lifecycle, and there is great uncertainty in the telecommunications market given the potential proliferation of LEO megaconstellations and competition from terrestrial 5G services. GEO communications companies are therefore hesitant to make decisions about their future investments in satellites even as their current satellites run low on propellant to maintain their orbits. Relocation services allow them to delay their decisions and wait for more certainty without losing revenue streams.

Even if these satellites manage to continue normal operations by using relocation services, they cannot operate indefinitely without losing market share because the price per bit will drop and their capacities will remain stagnant; eventually, relocation services will no longer be able to sustain the market, and new GEO satellites will be launched. As this happens, demand for relocation services will drop as new satellites will have full fuel tanks; these satellites will also more likely use electric propellant to maintain their orbits, meaning they are less likely to require relocation services in their lifecycle. However, even though GEO replenishment happens in waves, it never fully disappears, so a small market segment may still exist beyond this 8–10 year window and then grow again in another decade.

Commercial services to relocate satellites from LEO to GEO are unlikely to materialize in the timeframe of interest. Relocating from LEO to GEO using electric propulsion can take 6–8 months or longer; this is time that a commercial telecommunications satellite is not transmitting data and therefore not generating revenue. Even with cost savings by using a cheaper launch to LEO and a more efficient transit to GEO, the net-present value for using a direct flight to GEO is better for the company. In contrast, a nuclear thermal tug would take a matter of days to transfer a satellite from LEO to GEO. However, we believe that nuclear thermal propulsion, despite recent progress, will face many technological and regulatory hurdles, making its efficacy and profitability in the next 10 to 15 years unlikely.

Relocation in LEO (principally deorbiting satellites) is an emerging business in that small companies globally (none of which are mature in the United States) are offering services. However, the business case currently does not close by a wide margin, in the sense that the sellers want to charge significantly more than the potential buyers would want to pay; current service providers aim to charge millions of dollars to deorbit a satellite that only costs hundreds of thousands to build and launch.

This dynamic may change if governments require that satellite operators deorbit non-functioning satellites within some timeframe after they are non-operational. This will create a market for deorbiting services. Given that there is stated government interest in space safety and sustainability in both Europe and Japan, the governments in these countries are likely to announce regulations and policies. However, this is unlikely if countries with the greatest number of objects in space (Russia, the United States, and China) do not commit to similar regimes; it is also unlikely that any country would place such a heavy cost burden on a private company to purchase deorbiting services. Unless the governments agree to cover some or all the costs of de-orbiting, regulation to deorbit satellites and reduce the risk of collision in LEO is more likely to drive innovation in passive deorbit technologies than it is to drive costly LEO relocation services.

The economics of relocating satellites in GEO—whether for commercial or national security reasons—is evident. GEO is considered a limited natural resource, and even if governments are not willing to pay for debris removal services or force private companies to use them, private companies would be willing to pay to clear a GEO orbital slot so it can be re-used. Docking with and removing a single object from GEO also requires less delta-V than most maneuvers in LEO, so the price for such operations in GEO would be comparable to LEO.

3. Future of R3: Refuel

In the near future (less than 10 years), satellite operators are more likely to purchase an orbit maintenance service like the MEV than transfer fuel to satellites. Current satellites are not designed to be refueled easily, so an operation to reach a fuel valve would at least require cutting through insulation and other operations that would be perceived as risky even after a successful demonstration through a program like NASA's RSGS. Given the diversity of in-space fuel types, it would be difficult for a provider to service enough clients with one servicer to make refueling profitable.

Without a persistent platform or fuel depot from which to operate, refueling will likely be a niche market of which few outside of government entities will take advantage. A fuel depot in GEO may be more likely to be successful than one in LEO because the diversity of LEO orbits and the delta-V required to change among them make it difficult to operate; in contrast, most vehicles in GEO can be reached with relatively small impulses. A platform in LEO that also operates as a fuel depot could be successful, especially if it takes advantage of the supply chain that replenishes the ISS; however, we think such a platform would be unlikely given the lack of a market for a station currently (Crane et al. 2017).

To the best of our knowledge, no major sovereign exploration campaigns are considering in-space refueling in the next 10–15 years because they cannot adequately weigh the value proposition. No company currently offers services to transfer a payload that is entirely fueled for use in space; until that happens regularly, decision makers are unlikely to make any changes to elements of space.

We believe military operations could drive the market for refuel services. Increased maneuverability would lower the lifecycle cost of targeted observation campaigns, giving refueling a tactical advantage. However, a fuel depot in space may present too much of a risk or vulnerability to anti-satellite weaponry, so a military may think twice before investing in one.

R&D is underway for off-Earth mining and in-space propellant production (and resultant refueling). In our assessment, given technology readiness levels, the timeline for this activity is well over a decade (Lal et al. 2018; Colvin et al. 2020).

4. Future of R4/R5: Repair and Replace Parts

Because the first generation of satellite servicing will be the most difficult, and current satellites are not designed to be repaired, we believe that complex repair or replacement of parts missions may begin to be explored and demonstrated, but will likely not be the norm for more than a decade. Furthermore, we do not expect complex, invasive repair missions to be the norm once satellite servicing does become more mainstream; we believe satellite modularity will help simplify operations and make plug-and-play modules more common (i.e., R5: Replace Parts will be a regular operation before complex R4: Repair). We do not foresee the need for space robots to solder individual components on a circuit board or carry breadboard-level components, though manufacturing small parts with a 3D printer could be more cost-effective than a repair system carrying extra parts wherever it goes.

Given the high cost (hundreds of millions, if not billions of dollars) of launching and replacing satellites, there is significant R&D underway, both within government and the private sector, for in-space repair. Depending on the kind of repairs needed, many more advances are needed in modularity, interface standards, and robotics to make this a routine activity in the next decade and beyond.

If efforts to develop modular satellites succeed, on-orbit repair would be more commonplace. However, changing the culture of satellite design may take time, even if interface standards are developed and adopted quickly. Satellite manufacturers will likely not experience pressure from their customers to fundamentally redesign their standard satellite buses. Modularity in payloads, especially antennas, may be more commonplace in 10 years as robotics advances make larger antennas possible and operators need to provide more rapid data rates (see Section 6: Future of Assembly).

5. Future of R6: Recharge

The market for recharging services is likely too much of a niche and not steady enough to be a service provided on its own (much like ultra-close inspection). The insurance payout for a loss of power on a commercial satellite would be a more attractive short-term option than a mission solely to recharge a satellite.

In light of the strategic uses for recharging satellites and other applications of space-based electric power transfer, military applications for these capabilities could grow. This growth depends on many factors, including whether such capabilities provide a tangible strategic advantage or resilience in the face of a known threat, acquisition reform, and the risk attitudes of military personnel.

6. Future of Assembly

Assembly is one of the longest standing OSAM activities, with the United States having led the assembly of the largest structure in space (ISS), and China intending to do something similar soon. Activity in this area is led by governments, with government agencies such as NASA conducting studies—together with private sector contractors—to assemble the next big telescope in space or test assembly technologies in space.

Assembly is likely an area that will grow—not because it saves money but because it allows for capabilities that are infeasible to launch from Earth. One area that might be more common in the next 10 to 15 years is self-assembly of communications satellites. The mass savings and potential for larger antennas and therefore higher data rates could provide enough incentive to develop the modularity and boom technology needed to warrant pressure from operators on manufacturers to assemble in space, although the technology is still further behind than most basic satellite servicing technologies.

We foresee that the technical capability to construct the next great observatory in space will be within the United States' grasp within the next 10 to 15 years; however, the will to construct such a telescope may not materialize until well after the launch of the James Webb Space Telescope. A radio telescope, which requires far less precision and can be expanded over time, is more easily constructed. Technology demonstrations in assembly operations are well under way through existing Small Business Innovation Research programs.

Persistent platforms in LEO may not meet the needs of enough customers to be sustainable as private endeavors. The variety of orbit requirements for some applications makes it difficult to satisfy enough users, and competing platforms could create supply chain issues. If a follow-on to the ISS is built, it may serve enough needs but would likely require significant subsidy from the U.S. Government (Crane et al. 2017).

However, a platform in GEO could potentially serve many customers over a specific continent, and that platform could be expanded over time to meet the power and pointing requirements of those on board. The revenue generation, cost savings, and certainty in the communications market could provide enough incentive for such a platform to exist, but likely not for at least 10 more years.

7. Future of Manufacturing

In-space manufacturing, specifically that of things such as ZBLAN fiber in space for use on Earth, is a rapidly advancing area in the commercial sector, with R&D activity (co-funded by the government and the venture community) primarily in the United States. These companies are eager for global business and happy to open branch offices in other countries. In the next decade, it will likely be feasible to manufacture increasingly more complex systems in space, though the utility of objects manufactured in space for use in space may take more time to be realized than products created in space for use on Earth.

The search for "killer apps" for manufacturing in space for Earth and other advances in microgravity research will likely drive the development of in-space manufacturing, which will aid in the advancement of manufacturing in space for space. Much of the research and testing for these technologies will be conducted on the ISS (and on the private platforms expected to be in place after it is deconstructed).

In the 10–15 year time-horizon of interest, we do not foresee a market for typical satellites to be manufactured wholly in space. While some argue that satellites can be 3D printed on-demand in space and deployed where they need to be, the commercial small launch industry will likely be a more attractive option to quickly deploy a satellite; such applications are primarily military-related. The complexity of even small satellites is still too great for in-space manufacturing technologies and will likely remain so over the next decade. Some combination of basic manufacturing and assembly may undergo research and experimentation, but we do not foresee whole circuit boards and instruments being manufactured and deployed from a platform in the next 10 to 15 years.

While ISRU is likely to be a critical component of human space exploration campaigns beyond Earth orbit, studies show that the falling launch costs will make it difficult for propellant produced on the Moon or derived from asteroids and delivered to LEO or GEO to be profitable. Propellant derived on the lunar surface for use on the lunar surface may be cheaper than delivering it from Earth, but as Colvin et al. (2020) show, the technology to extract water from lunar regolith is at least 5 to 10 years from deployment.

Human life support systems are likely to utilize on-orbit manufacturing to bolster the reliability and longevity of those systems. It will likely be less costly to 3D print a part rather than bring to enough spares to ally all potential risks of breakdowns for a trip to Mars.

8. Uncertainties

Given the uncertainty in the current markets, government plans, and investment in technology development, it is difficult to predict the future of OSAM, but there are many pathways for OSAM to develop more rapidly than we have described in this chapter. Some pathways have been discussed broadly in Chapters 3 and 5, and some aspects are worth revisiting in more specific contexts here.

If governments begin to start investing in a long-term presence in cislunar space, even if they do not use an architecture that requires in-space infrastructure, in-space assembly, in-space refueling, and multiple launches, all areas of OSAM could increase in investment and progress. If governments use advanced concept selection and program management methods to map out key capabilities and goals, OSAM could prove to be an effective way to increase the value or utility derived from missions, increase resilience and real options during missions, and bolster the space economy with new applications (Corbin 2015; Ross 2009; Hassan 2005).

If the deconstruction of the ISS happens later than the current Administration has proposed, or if a follow-on platform begins operations such that there is no gap in R&D, OSAM can progress faster. If that follow-on platform has the ability to host payloads that require more power and might be deemed too risky to humans aboard the ISS (e.g., materials separation, industrial processing), we could see larger scale manufacturing systems being developed within the next decade. A testing platform is essential for shepherding technologies through the technology readiness level (TRL) “Valley of Death,” and we do not know what artificial barriers could be present with the ISS that an alternative platform could eliminate by enabling users to take more risks.

If there is an effort led by a sufficiently powerful entity (e.g., the U.S. Government or a large enough coalition of private companies) to evolve systems that limit the number of in-space propellant options (i.e., everyone uses LH2/LOX for chemical propellant, xenon for electric propellant), it could create enough standardization to reduce the uncertainty in refueling services and make refueling more appealing to decision makers. The fuel type selection would have many consequences on design choices across the supply chain, and there would be competition among the chemical alternatives.[8]

C. Future Capabilities by Select Country of Interest

In this report, we defined the scope of OSAM, described the prerequisite technologies to conduct OSAM, identified global entities engaged in OSAM activities, assessed what drives the progression of OSAM, articulated the value proposition for some use cases, and predicted where different activities in OSAM will be in the future. Based on the information collected, our overarching assessment is that OSAM is a relatively nascent field globally, but with potential to provide benefits to a wide range of operators and applications. Despite its potential, there is great uncertainty in technological and market progression over the next 10 to 15 years.

OSAM developments are not necessarily tracking markets. As the case studies in Appendix C show, for many countries in the world, OSAM is a national imperative for national security, prestige, and other reasons. Overlaying our understanding of the current state of technology and investment, the drivers that affect OSAM, and published national strategies (where available), STPI has assessed the current technology readiness of five countries we deem the most relevant, projected the *capabilities* they could have in the near-future (3–5 years), and forecasted downstream *competencies* they could have within the next 15 years (Figures 6-1–6-6). These judgements are based on capability, not a market to exercise such a capability regularly. We have ranked them on a modified stoplight chart to scale our confidence. The rankings for the United States (Figure 6-1) were prepared for context. The figures below build on the case studies in Appendix C, Tables 4-1 (country assessment on technology areas), 4-2 (country assessment on OSAM capabilities) and 4-4 (overall country assessment), and show that China and Russia are closest to the United States with respect to not just technology maturity of component technologies, but also current OSAM capabilities and projected future competencies. Germany has specialized in some areas, as has Japan. However, for the latter two countries, it is unclear based on their

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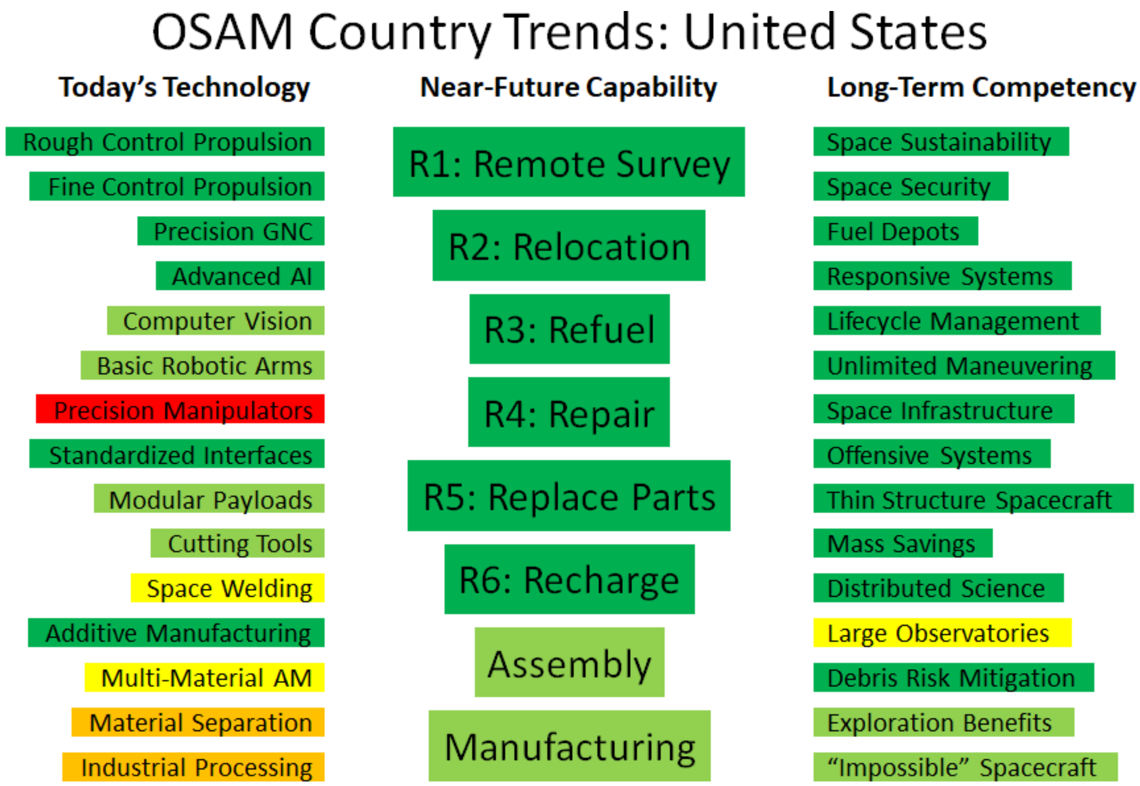
[8] For example, hydrazine is easy to store but toxic and not easy to derive from ISRU; LH2/LOX provides the highest specific impulse and can be derived from water extracted from the Moon but requires the most intense thermal management and is difficult to store without losing mass to outgassing; methane is easier to store, engines that use it are technologically simpler, and methane can be derived from the atmosphere of Mars, but cannot be derived easily from the Moon. Xenon would likely be the winner for the common electric propellant, but future supply may be too limited, and argon or krypton could provide good enough performance to meet most user needs.

current investment trajectories whether they will be able to achieve the competencies of interest.



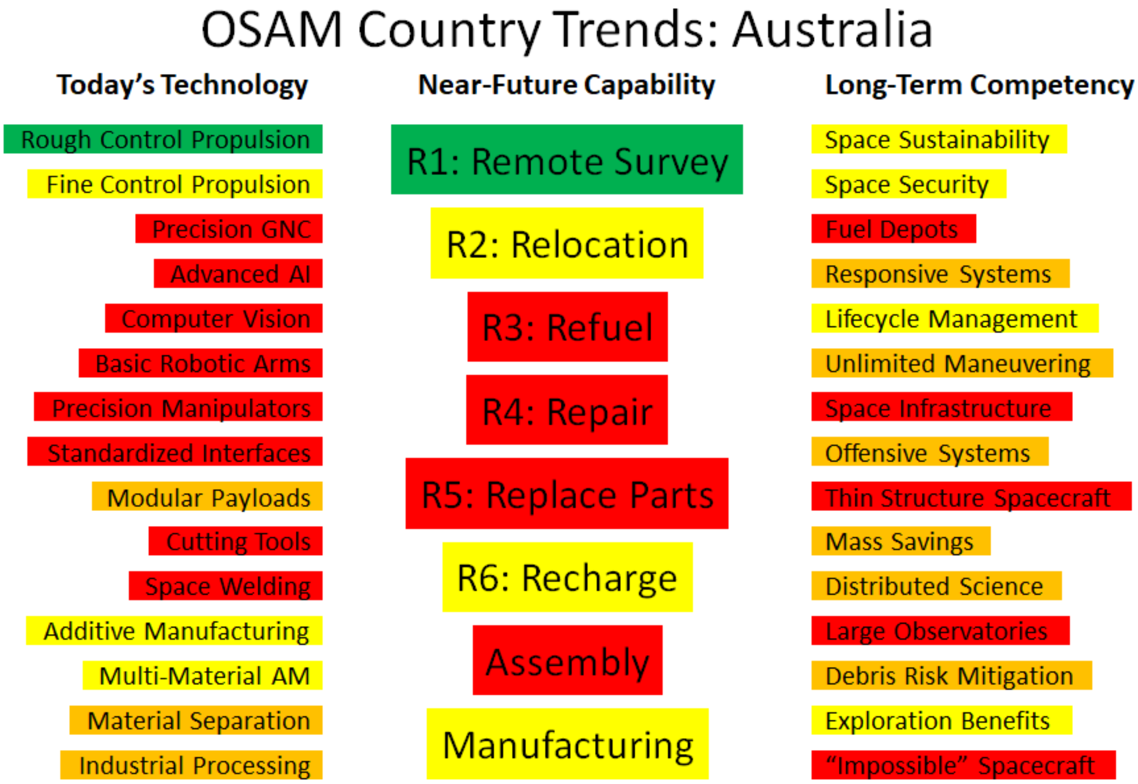
OSAM Country Trends: United States

Today's Technology	Near-Future Capability	Long-Term Competency
Rough Control Propulsion	R1: Remote Survey	Space Sustainability
Fine Control Propulsion		Space Security
Precision GNC	R2: Relocation	Fuel Depots
Advanced AI		Responsive Systems
Computer Vision	R3: Refuel	Lifecycle Management
Basic Robotic Arms		Unlimited Maneuvering
Precision Manipulators	R4: Repair	Space Infrastructure
Standardized Interfaces		Offensive Systems
Modular Payloads	R5: Replace Parts	Thin Structure Spacecraft
Cutting Tools		Mass Savings
Space Welding	R6: Recharge	Distributed Science
Additive Manufacturing	Assembly	Large Observatories
Multi-Material AM		Debris Risk Mitigation
Material Separation	Manufacturing	Exploration Benefits
Industrial Processing		"Impossible" Spacecraft

Note: The color scale has different meanings in each column:

- Today's Technology:
  - Green: The country has already used this technology in this application
  - Light Green: The country has demonstrated this technology for this application
  - Yellow: The country is actively working towards this technology
  - Orange: The country has announced plans or has made some progress in this technology
  - Red: The country does not have nor are they pursuing this technology
- Near-Future Capability and Long-Term Competency:
  - Green: Very likely this country will have capability within 5 years/competency within 15 years
  - Light Green: Likely this country will have capability within 5 years/competency within 15 years
  - Yellow: Somewhat likely this country will have capability within 5 years/competency within 15 years
  - Orange: Unlikely this country will have capability within 5 years/competency within 15 years
  - Red: Very unlikely this country will have capability within 5 years/competency within 15 years

Figure 6-1. Assessing Ability to Acquire Future Competencies: United States



OSAM Country Trends: Australia

Today's Technology

- Rough Control Propulsion
- Fine Control Propulsion
- Precision GNC
- Advanced AI
- Computer Vision
- Basic Robotic Arms
- Precision Manipulators
- Standardized Interfaces
- Modular Payloads
- Cutting Tools
- Space Welding
- Additive Manufacturing
- Multi-Material AM
- Material Separation
- Industrial Processing

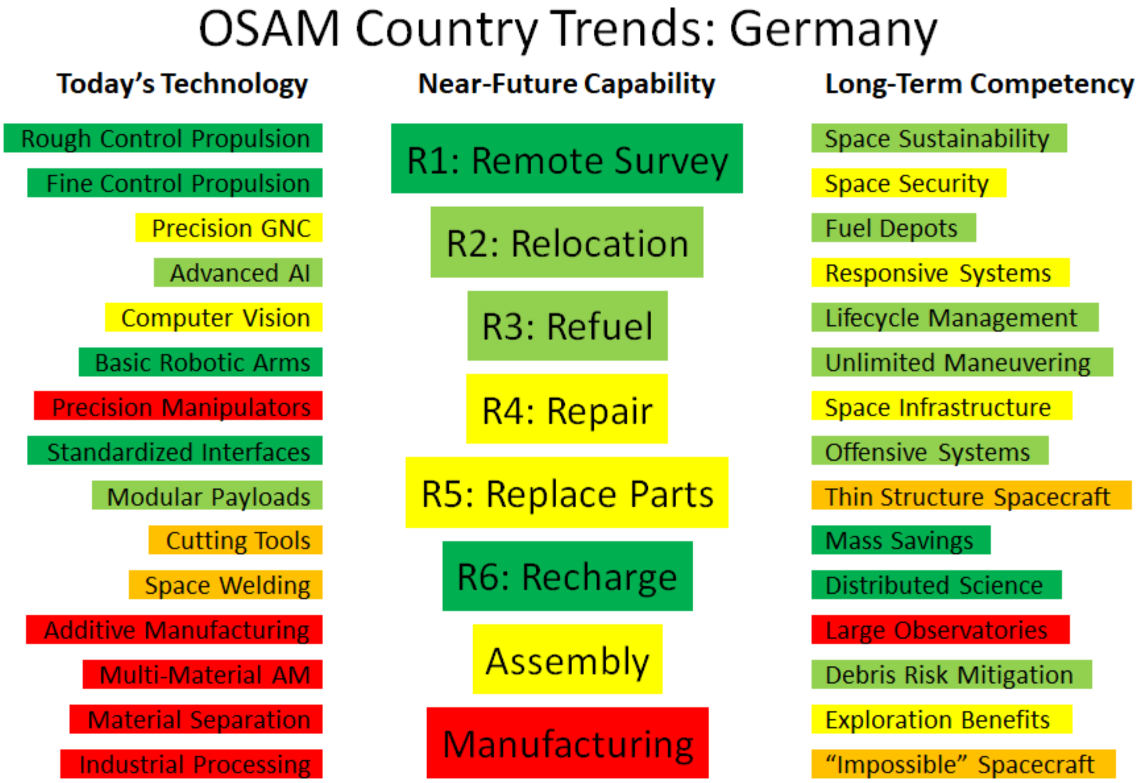
Near-Future Capability

- R1: Remote Survey
- R2: Relocation
- R3: Refuel
- R4: Repair
- R5: Replace Parts
- R6: Recharge
- Assembly
- Manufacturing

Long-Term Competency

- Space Sustainability
- Space Security
- Fuel Depots
- Responsive Systems
- Lifecycle Management
- Unlimited Maneuvering
- Space Infrastructure
- Offensive Systems
- Thin Structure Spacecraft
- Mass Savings
- Distributed Science
- Large Observatories
- Debris Risk Mitigation
- Exploration Benefits
- "Impossible" Spacecraft

Figure 6-2. Assessing Ability to Acquire Future Competencies: Australia



OSAM Country Trends: Germany

Today's Technology

- Rough Control Propulsion
- Fine Control Propulsion
- Precision GNC
- Advanced AI
- Computer Vision
- Basic Robotic Arms
- Precision Manipulators
- Standardized Interfaces
- Modular Payloads
- Cutting Tools
- Space Welding
- Additive Manufacturing
- Multi-Material AM
- Material Separation
- Industrial Processing

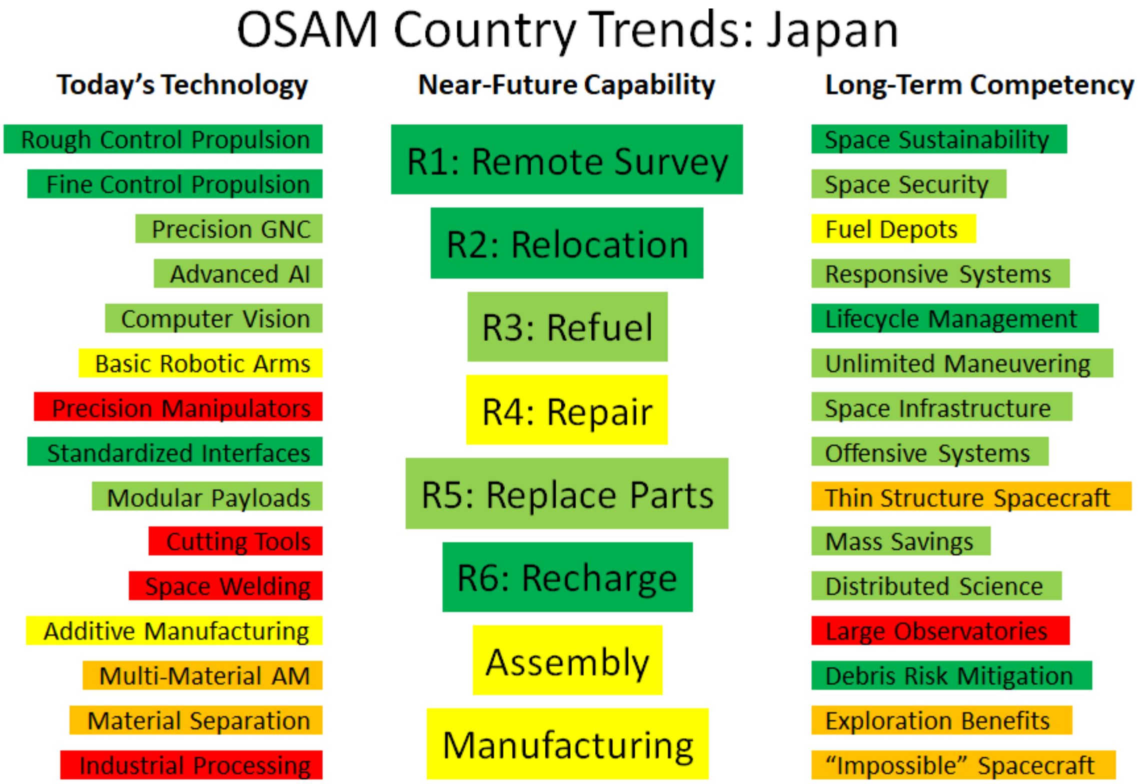
Near-Future Capability

- R1: Remote Survey
- R2: Relocation
- R3: Refuel
- R4: Repair
- R5: Replace Parts
- R6: Recharge
- Assembly
- Manufacturing

Long-Term Competency

- Space Sustainability
- Space Security
- Fuel Depots
- Responsive Systems
- Lifecycle Management
- Unlimited Maneuvering
- Space Infrastructure
- Offensive Systems
- Thin Structure Spacecraft
- Mass Savings
- Distributed Science
- Large Observatories
- Debris Risk Mitigation
- Exploration Benefits
- "Impossible" Spacecraft

Figure 6-3. Assessing Ability to Acquire Future Competencies: Germany



OSAM Country Trends: Japan

Today's Technology

- Rough Control Propulsion
- Fine Control Propulsion
- Precision GNC
- Advanced AI
- Computer Vision
- Basic Robotic Arms
- Precision Manipulators
- Standardized Interfaces
- Modular Payloads
- Cutting Tools
- Space Welding
- Additive Manufacturing
- Multi-Material AM
- Material Separation
- Industrial Processing

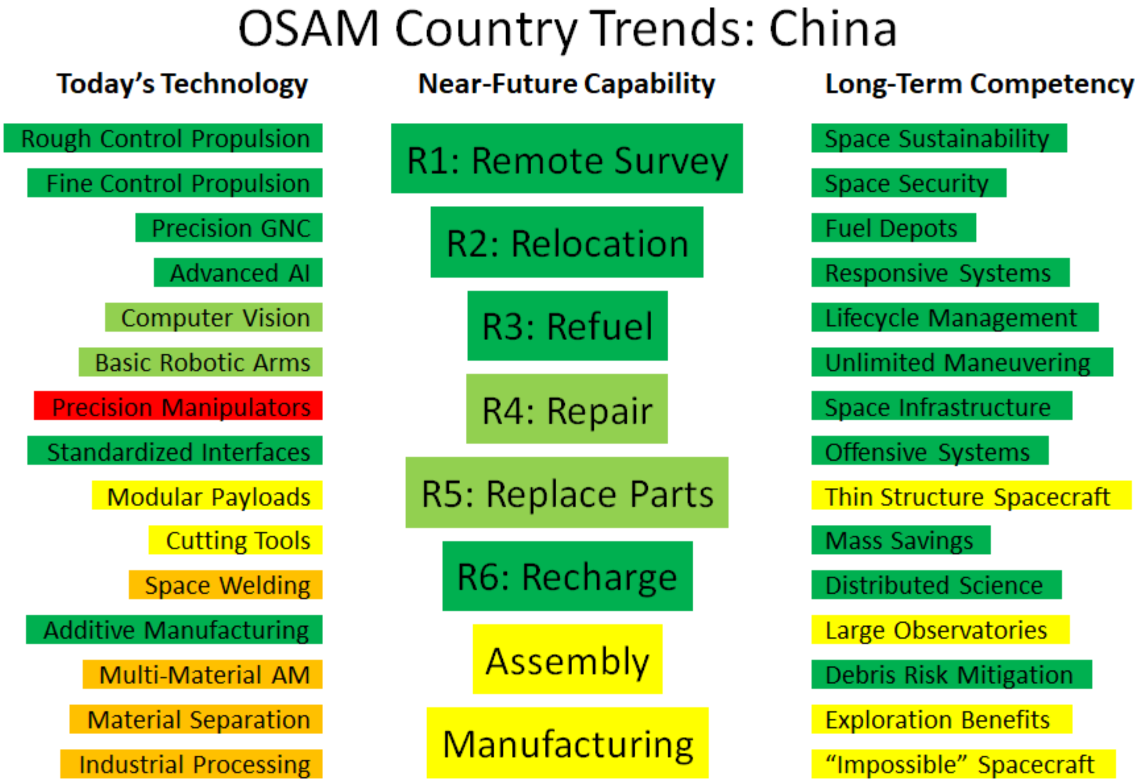
Near-Future Capability

- R1: Remote Survey
- R2: Relocation
- R3: Refuel
- R4: Repair
- R5: Replace Parts
- R6: Recharge
- Assembly
- Manufacturing

Long-Term Competency

- Space Sustainability
- Space Security
- Fuel Depots
- Responsive Systems
- Lifecycle Management
- Unlimited Maneuvering
- Space Infrastructure
- Offensive Systems
- Thin Structure Spacecraft
- Mass Savings
- Distributed Science
- Large Observatories
- Debris Risk Mitigation
- Exploration Benefits
- "Impossible" Spacecraft

Figure 6-4. Assessing Ability to Acquire Future Competencies: Japan



OSAM Country Trends: China

Today's Technology

- Rough Control Propulsion
- Fine Control Propulsion
- Precision GNC
- Advanced AI
- Computer Vision
- Basic Robotic Arms
- Precision Manipulators
- Standardized Interfaces
- Modular Payloads
- Cutting Tools
- Space Welding
- Additive Manufacturing
- Multi-Material AM
- Material Separation
- Industrial Processing

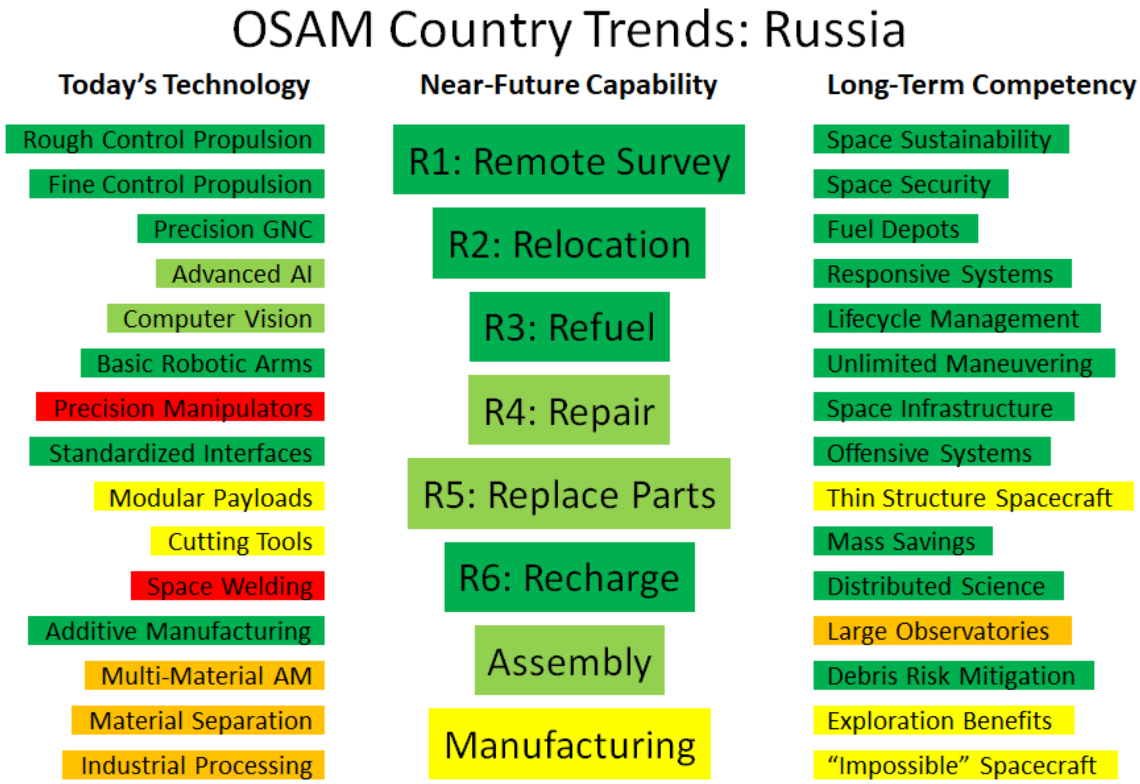
Near-Future Capability

- R1: Remote Survey
- R2: Relocation
- R3: Refuel
- R4: Repair
- R5: Replace Parts
- R6: Recharge
- Assembly
- Manufacturing

Long-Term Competency

- Space Sustainability
- Space Security
- Fuel Depots
- Responsive Systems
- Lifecycle Management
- Unlimited Maneuvering
- Space Infrastructure
- Offensive Systems
- Thin Structure Spacecraft
- Mass Savings
- Distributed Science
- Large Observatories
- Debris Risk Mitigation
- Exploration Benefits
- "Impossible" Spacecraft

Figure 6-5. Assessing Ability to Acquire Future Competencies: China



OSAM Country Trends: Russia

Today's Technology

- Rough Control Propulsion
- Fine Control Propulsion
- Precision GNC
- Advanced AI
- Computer Vision
- Basic Robotic Arms
- Precision Manipulators
- Standardized Interfaces
- Modular Payloads
- Cutting Tools
- Space Welding
- Additive Manufacturing
- Multi-Material AM
- Material Separation
- Industrial Processing

Near-Future Capability

- R1: Remote Survey
- R2: Relocation
- R3: Refuel
- R4: Repair
- R5: Replace Parts
- R6: Recharge
- Assembly
- Manufacturing

Long-Term Competency

- Space Sustainability
- Space Security
- Fuel Depots
- Responsive Systems
- Lifecycle Management
- Unlimited Maneuvering
- Space Infrastructure
- Offensive Systems
- Thin Structure Spacecraft
- Mass Savings
- Distributed Science
- Large Observatories
- Debris Risk Mitigation
- Exploration Benefits
- "Impossible" Spacecraft

Figure 6-6. Assessing Ability to Acquire Future Competencies: Russia

Appendix A. List of Interviewees

Agency/Entity Name	Name of Interviewee	Country	Date of Interview
AB5 Consulting	Betty Bonnardel	France	09/29/2019
Airbus	Yannick Jégo	France	10/25/2019
Altius Space Machines	Jonathan Goff	United States	10/05/2019
Argotec	Valerio di Tana	Italy	10/25/2019
Astroscale	Nobu Okada	Japan	10/07/2019
Astroscale	Jason Forshaw	Japan	10/07/2019
Astroscale	Charity Weeden	Japan	08/07/2019
AVS	Alberto Garbayo	Spain	10/25/2019
AVS	Eric Van Every	Spain	10/25/2019
AXA XL	Chris Kunstadter	United States	08/29/2019
Ball Aerospace	Melissa Sampson	United States	09/20/2019
Cabinet Office, Government of Japan	Issei Matsubara	Japan	02/25/2020
CHANDAH	Adil Jafry	United States	08/07/2019
Deimos	Noelia Sanchez Ortiz	Spain	10/25/2019
DLR	Marc Jochemich	Germany	10/03/2019
DLR	Daniel Noelke	Germany	10/03/2019
D-Orbit	Eleonora Luraschi	Italy	10/25/2019
Effective Space	Daniel Campbell	UK	10/07/2019
Effective Space	Michael Pollack	UK	10/03/2019
ESA	Andrew Wolahan	Europe	09/13/2019
ESA	Antonio Caiazzo	Europe	09/13/2019
ETRI	Byoung Sun Lee	Korea	10/25/2019
ExoAnalytic	Phillip Cunio	United States	10/15/2019
ExoAnalytic	Brian Flewelling	United States	10/15/2019
FCC	Karl Kensinger	United States	10/08/2019
HEO Robotics	William Crowe	Australia	10/03/2019
iBoss GmbH	Joerg Kreisel	Germany	10/01/2019
Infinite Orbits	Akshay Gulati	Singapore	08/26/2019
Inovor	Matthew Tetlow	Australia	10/21/2019
Italian Space Agency	Marco Tantardini	Italy	09/19/2019
JAXA	Hiroshi Ueno	Japan	09/12/2019
JAXA	Kota Umeda	Japan	09/12/2019

Agency/Entity Name	Name of Interviewee	Country	Date of Interview
JAXA	Masami Onada	Japan	02/19/2020
Lockheed Martin	Rob Chambers	United States	08/30/2019
Luxembourg Space Agency	Marc Serres	Luxembourg	10/25/2019
Made In Space	Twyman Clements	United States	10/23/2019
Maxar	Al Tadros	United States	10/09/2019
Maxar	Atif Qureshi	United States	10/09/2019
Moog	Barry Safier	United States	09/28/2019
Nanoracks	Mike Lewis	United States	10/25/2019
Nasa Goddard	Benjamin Reed	United States	08/15/2019
NASA JPL	Rudra Mukherjee	United States	08/06/2019
New Zealand Space Agency	Tim Searle	New Zealand	10/09/2019
New Zealand Space Agency	Jonathan Mitchell	New Zealand	10/09/2019
NORSS	Ralph Disnley	UK	10/25/2019
Northrop Grumman	Jim Armor	United States	09/12/2019
OneWeb	Adrian Steckel	UK	10/25/2019
OrbitFab	Daniel Faber	United States	08/06/2019
Oxford Space Systems	Mike Lawton	UK	09/28/2019
Satellite Applications Catapult	Anastasia Bolton	UK	10/25/2019
Secure World Foundation	Brian Weeden	United States	11/25/2019
SES GS	Bryan Benedict	Luxembourg	09/30/2019
SES GS	Jon Bennett	Luxembourg	09/30/2019
Singapore Space and Technology Association	Lynette Tan	Singapore	10/25/2019
Space Logistics	Joe Anderson	United States	10/03/2019
Space Tango	Kevin DiMarzio	Space Tango	10/24/2019
Space.Tec	Rainer Horn	Germany	10/25/2019
Spaceable	Julien Cantegreil	France	10/07/2019
SpaceX	Patricia Cooper	United States	09/19/2019
SSTL	Andrew Cawthorne	UK	10/25/2019
SSTL	Martin Sweeting	UK	10/25/2019
Tethers Unlimited	Robert Hoyt	United States	08/05/2019
Thales Alenia	Flavio Bandini	Italy	09/25/2019
Twenty First Century Aerospace Technology	Wein Sun	China	10/25/2019
UK Space Agency	Andrew Ratcliffe	UK	09/29/2019

Appendix B. Interview Protocols

Questions for Organizations Conducting OSAM

Section 1: Informational Background on Organization

1. Organization
    a. Please describe what your organization does, how and why?
    b. What are your current research/development efforts and capabilities?
    c. What are your product lines and where are they at on a development continuum?
    TRL? (Technology readiness level)

    Timelines?

    Next steps? (e.g., in-space demos)
2. Employees:
    a. How many employees (FTEs) do you currently have?
    b. How many FTEs do you expect to add in the coming years?

Section 2: Money/Current and Future Funding

3. Funding background:
    a. How much funding do you have?
    b. Who are your current funders?
    c. How much funding do you need in the coming years?
    d. Where else do you think you can get this funding?
4. Revenue: (this information will be kept confidential)
    a. How much revenue do you generate today, if any?
    b. What do you expect your revenues to be in the coming years?
    c. What is your expected pay structure for the services you offer?

Section 3: Customers & Suppliers

5. Supply:
    a. Who are your current suppliers?
    b. What future suppliers might you need?
6. Customers:
    a. Who are your current customers/users of products?
    b. What future customers are you aiming for?

Section 4: Partnerships vs. Competition

7. Partnerships:
    a. Do you have any collaborations or partnerships with other organizations?
    b. With which organizations do you have any collaborations or partnerships?
    c. What are the goals of these partnerships?
    d. What future partners might you seek/benefit from? What makes you seek these partnerships?
8. Competition:
    a. Who do you see as your current and future competitors (or organizations proposing similar offerings to yours?)

Section 5: Company R&D Needs

9. R&D Breakthroughs:
    a. What R&D breakthroughs are you dependent on to get to your vision?/ What additional developments would enable you to increase scale or capabilities?
    b. What is the status of these areas/technologies?
    c. Overall, what technical factors drive/inhibit developments in OSAM?

Section 6: OSAM Landscape

10. Company in relation to their country:
    a. How does your organization's capabilities compare to other organizations' capabilities in your country?
    b. How (if at all) does your work fit with *your* country's overall plans in space?
    c. Does your country have any expressed interest in the Moon, for scientific research and exploitation? If so, are there any OSAM activities that are specifically connected to you lunar aspirations?
11. Effect of OSAM:
    a. Going beyond your organization, where do you see the greater OSAM landscape in 10-15 years? / What capabilities do you think OSAM would be able to deliver in space in this time frame and what can these capabilities do for the space sector? (i.e. what would be feasible if these capabilities were to exist)?
    b. (For manufacturing) What products do you see being manufactured in space for use on Earth that would beat the cost of launch and return?
12. Demand for OSAM in the future:
    a. What do you see as the demand for OSAM?
    b. What are the key factors that would accelerate this future?
    c. If the OSAM vision doesn't come true, why would that be? What are the key impediments/roadblocks?

    d. What trade-offs do you see? (e.g., does a drop in launch cost negate the business case for some R5AM activities, or success of LEO constellations reduce interest in GEO assembly of satellites)?
    e. How would you describe the OSAM market?
13. Enablers/Disablers of OSAM
    a. What are some of the barriers (e.g., space platform limitations, safety standards, etc.) to conducting more research in OSAM (both basic and applied industrial processes)?
    b. What other factors that we don't think about much today may be important in the future? (e.g., will space debris be an even bigger concern if large persistent platforms are being hit by debris from irresponsible operators?) Are there unseen political issues that could become more prominent because of OSAM?)
14. International
    a. What international OSAM activities are you aware of?

Questions for Potential Customers and Users

Section 1: Impact of OSAM on customer/user:

1. What do OSAM capabilities (as currently being advertised) mean for your organization?
2. How long do you think it would it be before they come to fruition?
3. How do you plan to incorporate OSAM capabilities into future missions as part of your trade space exploration and design process? How will OSAM capabilities change the way you do things or think about operations in space?

Section 2: Demand for OSAM:

4. What do you see as drivers/impediments to achieving this vision?
5. Realistically speaking, what do you see as the demand for OSAM?
    1. What factors are driving this demand?
    2. What factors might change this demand?

Section 3: Response to OSAM:

6. How does OSAM factor into your organization's near-term plans?
7. Would you purchase OSAM services? Which ones and why?

Section 4: Catalysts for transitioning to OSAM

8. What circumstances would create the "tipping point" necessary to make a transition from traditional versus OSAM approaches? What level of risk or cost reduction do you need to have to be secure in that decision?
9. What regulatory circumstances would cause you to consider purchasing OSAM services (e.g., mandatory controlled satellite deorbit) rather than continuing with

the status quo? Are the consequences of such regulatory changes/burdens potentially catastrophic to your business model as it exists today?

Questions for Organizations Funding OSAM

Section 1: Background Information on Organization:

1. What are the factors driving your organization’s interest in OSAM?
2. What national strengths (technical, institutional, commercial) do you/your government intend to leverage in developing your OSAM programs?
3. How do you plan to incorporate OSAM capabilities into future missions as part of your trade space exploration and design process? How will OSAM capabilities change the way you do things or think about operations in space?

Section 2: Money/Current and Future Funding:

4. In the OSAM sector, what do you fund, to what levels of funding, and why? How does OSAM fit with national space priorities?
5. What funding levels do you expect to expend in the coming years? (to the extent you can tell us)
6. (To the extent you know) What other sources of funding do organizations that you fund have?

Section 3: Customers and Suppliers:

7. What do you see as the demand for OSAM?

Section 4: Partnerships vs. Competition:

8. What OSAM-related partnerships do you have (organizations, countries)? For each partnership, what is the goal, and is there any funds-exchange? Technology exchange? Facilities usage?
9. How is your country’s OSAM program connected to other projects and interests? For example: lunar materials utilization; scientific applications; defense applications; communications industry growth; or others such as space-based solar power?

Section 5: Company R&D needs

10. What further functionalities (e.g., lower cost to do bigger missions, higher lifecycle output for refuel-able satellites) can these capabilities enable? Which ones do you realistically see your organization leveraging?

Section 6: OSAM Landscape:

11. Above and beyond what you fund, what OSAM capabilities do you see coming to fruition in 10-15 years?
12. Effect of OSAM:
    a. What do you see as the key factors (e.g. growth in demand for deorbit services, major government funding programs, regulatory changes, etc.) that would accelerate this future?

   b. What products do you see being manufactured in space for use on Earth that would beat the cost of launch and return?

13. Demand for OSAM in the future:
    a. What do you see as the key impediments (e.g., fall in the cost of launch, success of LEO constellations over GEO life extension, etc.)?
14. Enablers/Disablers of OSAM
    a. What are some of the barriers (e.g. space platform limitations, safety standards, etc.) to conducting more research <u>in OSAM (</u>both basic and applied industrial processes)?
    b. What are some of the barriers (e.g., space platform limitations, safety standards, etc.) to conducting more research <u>in manufacturing</u> (both basic and applied industrial processes)?
    c. What other factors that we don't think about much today may be important in the future? (e.g., will space debris be an even bigger concern if large persistent platforms are being hit by debris from irresponsible operators? Are there unseen political issues that could become more prominent because of OSAM?)

Appendix C. Country Case Studies

Europe

Germany

- Context: Overall Space Landscape
    - ESA Investment
        - Germany, via its Federal Ministry of Economics and Technology (BMWi) and its Federal Ministry of Transport and Digital Infrastructure (BMVI), will provide 3.3 billion euros to ESA's budget in the next 5 years, accounting for 22.9 percent of total ESA funding, and nearly four times the amount it spends on the German Aerospace Center (DLR), the country's national space agency (DLR 2019a; ESA 2019h). Germany will be the largest contributor to ESA's budget beginning in 2020, after having trailed France for the previous 5 years (ESA 2019f).
        - Of those 3.3 billion euros, about 578 million will go to ESA's Science program; 690 million to Earth observation, climate control, and Global Development Aid; 322 million to telecommunication; 94 million to Space Situational Awareness (SSA); 160 million to new technologies; and 533 to exploration and related technologies (ESA 2019b).
    - DLR Space Funding
        - In 2018, DLR's budget for its space administration and related programs was 285 million euros. In 2019, DLR's budget will increase to about 300 million euros.[9]
        - In 2018, million euros went towards human spaceflight and exploration; 48 million went towards Earth observation; 56 million went towards space science projects; 78 million went towards research and development for space systems, including robotics; and 54 million went towards satellite communications.

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[9] Based on Interview(s)

        - When comparing DLR's national funding to Germany's investments in international ESA projects, Germany clearly focuses on independent development of robotics, sensor technology, AI, and satellite communications, which are vital enabling technologies for OSAM.

- OSAM Landscape
    - Historical Missions: Germany has one of the longest track records of in-space robotics and OSAM related activities in the world.
        - The first on-orbit demo of German robotic technology, RObotic TEchnology EXperiment (ROTEX), took place during the D2 mission in 1993 on a US Space Shuttle.[10]
        - In 1997, ETS VII was launched by JAXA as an experimental technology demonstrator to verify advanced robotics for close proximity operations and satellite servicing. Germany contributed a number of critical components in the areas of manipulator control, virtual reality, and simulation.[11]
        - At the end of the 1990s, the first commercial OSAM company, Vanguard Space, was set up in Germany with the objective of providing space tug services. The company shut down a few years later.[12]
        - From 2001 to 2005, DLR led multiple concomitant activities, including workshops and studies, related to OSAM in close collaboration with CSA and JAXA.
        - In 2004, DLR launched the Robotics Component Verification on ISS (ROKVISS), in order to flight-qualify DLR robotic joints and an arm. In 2005, the ROKVISS experiment hardware was mounted outside the ISS. The ROKVISS arm performed both fully autonomous and telepresence operations until 2010, when the mission was declared a success and terminated, leading to the removal of the arm from the ISS (DLR 2019c).
        - Starting in 2010, DLR funded an orbital servicing mission called the Deutsche Orbitale Servicing Mission (DEOS) to practice how to complete maintenance tasks, particularly refueling, to extend the

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[10] Based on Interview(s)

[11] Based on Interview(s)

[12] Based on Interview(s)

service life of satellites. The planned mission involved a ground station overseeing operations, a client, and a servicer, and each was to be developed and maintained by a private organization (DLR 2019d). The mission was canceled around 2016, prior to the launch of either satellite.[13]

    - Also in 2010, the Intelligent Building Blocks for On-Orbit Satellite Servicing and Assembly (iBOSS) initiative began as a DLR-funded collaborative research project between several research institutions.[14] The technology developed during the course of the project included modular building blocks for satellites, interfaces for connecting blocks to one another and to satellites, a software package to model a satellite, and a simulation environment for those modeled satellites.[15] Two private firms, iBOSS GmbH, which commercialized the iBOSS technologies, and iBOSS Solutions GmbH, which commercialized the related engineering services, were created in 2017 (iBOSS GmbH 2020a).

  - Current and Planned Activities
    - DLR has no currently active OSAM mission, so is working on component technologies, including robotics and satellite communications. It is also helping to develop supporting and enabling technologies, by focusing on cooperative design and related technologies.[16]
    - Because DLR focuses on commercializing space technologies, they are currently trying to leverage the traditional strengths Germany has in robotics and on-ground manufacturing. For example, Germany's KUKA robots are used the world over, including in the United States, to test OSAM capabilities. DLR wants to use the efficiency of the German terrestrial manufacturing sector to produce satellite components at scale to reduce the cost of creating satellites capable of servicing and being serviced.[17]
    - Germany will continue to fund ESA missions, particularly Earth observation missions and missions that deploy robotic technologies,

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[13] Based on Interview(s)

[14] Based on Interview(s)

[15] Based on Interview(s)

[16] Based on Interview(s)

[17] Based on Interview(s)

due to perceived benefits to the German economy.[18] For this reason, Germany will be contributing to the first European OSAM mission, Active-Debris Removal/In-Orbit Servicing (ADRIOS; ESA 2019a).

- iBOSS GmbH is commercializing core technologies developed through the DLR iBOSS initiative by leveraging international patents and licensing of other iBOSS technologies.
- Specifically, iBOSS GmbH is currently focusing on marketing the intelligent Space System Interface (iSSI). The iSSI is a TRL 6 coupling set. The iSSI fully modular and multi-functional; it provides mechanical, data, and power connections, with an optional thermal interface (iBOSS GmbH 2020b). The iSSI allows for any manual or robotic coupling, reconfiguration, or extension of systems, both on ground and in space. It is currently available as a lab model for testing and system studies, and is currently in use on-ground by users on multiple continents. When the iSSI is used in space, the objects could be a client and a servicer, two modular building blocks as parts of a larger satellite, a robotic end effector and a block, and more, so long as both objects have iSSI integrated into their structures.[19] Therefore, iSSI only facilitates cooperative servicing. iBOSS GmbH is planning on flight-testing iSSI for servicing missions in Q4 2020 and Q1 2021.[20]
- iBOSS GmbH also manages IP for building satellites using iBOSS functional Building Blocks (iBLOCKs), also developed during the DLR iBOSS initiative. iBLOCKs are cubic building blocks, designed to carry distinct subsystem components and with connectivity provided by integrated iSSIs. The iSSIs allow for easy configuration of space systems on ground, as hosted payload blocks or even fitted together to form entire satellites (DLR 2019b). iBOSS GmbH is planning to begin commercializing iBLOCKs once the iSSI becomes more widely used.[21]
- Project MOONRISE is a consortium between the Lazer Zentrum Hannover e.V. and the Institute of Space Systems at the Technical

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[18] Based on Interview(s)

[19] Based on Interview(s)

[20] Based on Interview(s)

[21] Based on Interview(s)

        University of Braunschweig, in partnership with DLR, focusing on melting Moon rocks for use in manufacturing on the lunar surface.

  - Key Institutions
    - Government: DLR is working in coordination with its 50 research institutes to develop the component technologies necessary for OSAM activities, including advanced robotics (through the Robotics and Mechatronics Center; RMC) and manufacturing (DLR 2020).
    - Private: iBOSS GmbH is the most prominent example of German commercialization within OSAM, and is a member of CONFERS. They took a servicing interface developed during a DLR initiative to create a modular satellite architecture. They characterize the iSSI as the future USB-port for OSAM, and have built the supply chain to mass-produce it at low cost per unit. In addition, iBoss GmbH want to commercialize iBLOCKs as a plug-and-play system for satellite manufacturing.
    - Private: The German Research Center for Artificial Intelligence (DFKI GmbH) is a private company that works closely with the University of Bremen and performs artificial intelligence research to enable autonomous robotic activity, both terrestrially and in-space (Robotics Innovation Center 2020).
    - Private: High Performance Space Structure Systems (HPS GmbH) leads a European consortium to build a large deployable reflector subsystem, including an arm and a reflector, called the Large European Antenna (LEA; HPS 2020).
  - Fit with Overall Goals
    - Germany sees space as an instrument of economic development and for the creation of high-paying jobs. OSAM is seen as a natural extension of Germany’s terrestrial robotic and manufacturing prowess.[22]
- Investment and Funding
  - Government

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[22] Based on interview(s)

    - Funding for OSAM-specific initiatives and projects is around 15 million euros a year.[23]
  - Private
    - iBOSS GmbH’s funding as yet is all internally generated, though specific numbers are undisclosed. The company generates operational revenues as of 2018.
- OSAM Partnerships
  - Partners and Goals
    - EU Commission: The Commission coordinates two Strategic Research Clusters relevant to OSAM: one for robotics, and one for electric propulsion. The consortium for the Program Support Activities (PSA) for robotics, PERASPERA, includes DLR, CNES, UKSA, ASI, CTDI, POLSA, and ESA, which coordinates the activity. DLR is taking a key role in defining the roadmap of PERASPERA. More than fifty companies and research organizations are working on the Space Robotics SRC, including activities on orbital support services like refueling and life extension, on-orbit assembly of large telescopes and satellites, and reconfiguration of satellites.[24] In addition to strategically developing key technologies for OSAM, PERASPERA also seeks to define guidelines and standards for commercial OSAM activities via the European Operations Framework (EOF). The EOF seeks to establish regulations for OSAM activities as collaborative efforts between agencies, industry, operators, and insurance companies.
  - Gaps Addressed
    - EU Commission: The PERASPERA partnership allows Germany to define programmatic and strategic roadmaps in a central role within a European consortium for the development of in-space robotic capabilities, including for use on OSAM missions.[25]
- Drivers
  - <u>Germany’s traditional strength in robotics:</u> Europe’s space efforts in PERASPERA has three tracks: the orbital track, the planetary track, and the

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[23] Based on interview(s)

[24] Based on interview(s)

[25] Based on Interview(s)

    common building block track, which provides components to be used by the orbital and planetary tracks. Germany leads these efforts in part by virtue of its traditional strengths in robotics and manufacturing.[26]

- Barriers
    - Funding: Since much of Germany's space efforts work via ESA or the Commission, funding is split between all areas of interest, which are in part dictated by other European nations. This sometimes restricts the ability of German activities to get funding DLR requests.[27]

France

- Context: Overall Space Landscape
    - The National Centre for Space Studies (CNES) is the French governmental space agency, and is under the supervision of the French Ministries of Defense and Research. In 2015, CNES defined five strategic focuses through 2020: Ariane, the country's launch program intended to give France independent access to space; Sciences, encompassing basic research; Observation, specific to Earth; Telecommunications; and Defense, focusing on high-resolution optical observation, electronic intelligence, secure telecommunications, and space situational awareness (CNES 2015).
    - France will create a new military space command, which will likely drive its use of OSAM technologies (Mallet 2019).
    - Starting in 2020, France will be the second largest financial contributor to ESA, behind Germany, providing 2.664 billion euros over 5 years, accounting for 18.5 percent of ESA's total budget (ESA 2019h).
    - The specific OSAM activities of CNES are largely unknown. Publicly available information is scarce, and representatives from CNES denied a STPI request to discuss French efforts in OSAM. There may be more CNES activities in OSAM beyond those discussed here.
    - The private landscape consists of a small number of large, mature companies, and a set of companies just beginning to develop.
- OSAM Landscape
    - Current and Planned Activities

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[26] Based on interview(s)

[27] Based on interview(s)

        - CNES
            - CNES is planning the CASTOR1 (Capacité strAtégique Spatiale de Télécommunication mObile et Résiliente) mission, which it views as a precursor to potential future missions to modify satellites on orbit. CASTOR1 will demonstrate a flexible antenna featuring on-demand beam shaping. CASTOR1 is particularly appealing to the defense sector in France for use during operations (CNES 2018).
            - CNES developed the Innovative DEorbiting Aerobrake System, which uses inflatable booms to increase the drag of a satellite, causing it to deorbit at the end of its lifespan within the 25-year span currently mandated by law. The system was deployed in space to deorbit a satellite for the first time in October 2018. The success of the system could reduce the demand for specialized servicers coming from the French government.
        - Share My Space
            - Share My Space provides space debris simulation and tracking services to satellite operators to inform decisions about when evasive maneuvers are necessary for the safety of the satellite.
        - Thales Alenia
            - Thales Alenia is currently performing two studies on OSAM, one for servicing and one for assembly, to determine what role in the ecosystem it can play. Its servicing study focuses in part on deorbiting technologies.[28]
            - Thales Alenia is aiming to have a ground demonstration of servicing techniques by 2023–2024, and in-space demonstrations by 2025–2026. The target customer is GEO operators.[29]
    - Key Institutions

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[28] Based on interview(s)

[29] Based on interview(s)

        - CNES: The national French space agency, CNES, is investigating the use of deployable booms and antennas, with an eye towards on-orbit assembly of booms and antennas in the future.
        - Share My Space
            - Share My Space is interested in developing the conceptual on-orbit debris collection service DRYADE, based on bio-mimicry (Share My Space 2019b).
            - Share My Space provides space debris simulation and tracking services to satellite operators to inform decisions about when evasive maneuvers are necessary for the safety of the satellite (Share My Space 2019a; Share My Space 2019c).
        - Thales Alenia: Thales Athenia is a Franco-Italian aerospace manufacturer, headquartered in France. It is 67 percent owned by the French company Thales Group and 33 percent owned by the Italian company Leonardo SpA. It is currently performing early stage studies of OSAM, focusing on deorbiting and assembly.[30] Thales Alenia is also a part of CONFERS.
    - Fit with Overall Goals
        - Based on the five strategic goals of CNES, OSAM would fit primarily within their Defense goal. However, the lack of specific information about the Defense programs makes it difficult to determine how important OSAM would be for them.
        - Thales Alenia views OSAM as in-line with their ability to provide comprehensive care for the satellites they manufacture.[31]
- Investment and Funding
    - Government
        - Funding for OSAM-specific projects is unknown.
    - Private
        - Thales Alenia: Specific numbers are unknown, but its OSAM studies are supported in part by ESA and the Italian space agency, ASI.

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[30] Based on interview(s)

[31] Based on interview(s)

        - Share My Space: Specific funding levels for the DRYADE debris removal mission are unknown.

- Partnerships
    - Partners and Goals
        - France funds ESA, and CNES partners with ESA on missions including the European Commission-funded and ESA-coordinated robotics strategic research cluster (SRC) PERASPERA.
        - Share My Space partners with the French public university École Polytechnique as a research collaborator on the DRYADE mission.
        - Thales Alenia's OSAM studies are funded in part by ESA and the Italian space agency, ASI.
    - Gaps Addressed
        - CNES cooperates with ESA and many other European space agencies through PERASPERA to coordinate efforts to develop in-space robotics across Europe.
        - Thales Alenia's funding from governmental agencies creates an upfront business case for OSAM studies that would not otherwise exist.
        - Share My Space's collaboration with École Polytechnique enables it to pursue ambitious research goals that it alone could not complete on the same timeline.
- Drivers
    - Defense: governmental agencies have some interest in OSAM capabilities for use on defense missions, which may generate early business cases for developing technologies that could then be marketed for commercial uses.[32]
- Barriers
    - Lack of prioritization: while OSAM may facilitate other missions of interest to CNES and the French government, there is no particular emphasis on OSAM, making development harder.[33]

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[32] Based on interview(s)

[33] Based on interview(s)

Italy

- Context: Overall Space Landscape
  - Italy will contribute 2.282 billion euros to ESA over the next 5 years, third most of any country and accounting for 15.9 percent of ESA's total budget (ESA 2019h).
  - In 2018, Italy announced changes to its space governance that established a ministerial space and aerospace committee, elevating issues related to space to the level of the prime minister (ResearchItaly 2018).
  - In 2019, the Prime Minister's Office released the "Government guidelines on space and aerospace," which focuses on expanding the commercial space sector by supporting increased technological production and attracting capital. National security is also identified as a key priority (Italian Prime Minister's Office 2019).
  - "In-orbit servicing" is specified as one of seven strategic sectors to receive particular emphasis in the Guidelines. The Guidelines highlight the importance of research and development of low-thrust propulsion, space object identification and tracking, docking, and intelligent robotic systems as part of the in-orbit servicing sector.
- OSAM Landscape
  - Current and Planned Activities
    - Italian Space Agency (ASI)
      - The Italian government, in coordination with ASI, has announced a set of guidelines for space and aerospace, which highlight the need for in-orbit servicing. In particular, the guidelines emphasize research and development of key technologies, including low-thrust propulsion, space object identification and tracking, docking, and intelligent robotic systems. The guidelines also recognize the importance of developing regulations to support in-orbit servicing (Italian Prime Minister's Office 2019).
      - ASI's primary focus in OSAM is on deorbiting and satellite repair. To that end, ASI funds studies performed by the Franco-Italian aerospace manufacture, Thales Alenia.[34]

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[34] Based on Interview(s)

    - ASI also funds and is a member of the PERASPERA consortium, a European Commission-funded effort to develop space robotics.[35]
- Argotec
    - Argotec is an aerospace engineering company specializing in small satellites. It is building two small satellites with autonomous remote inspection capabilities: one for NASA's Double Asteroid Redirection Test (DART) with an expected launch date in 2021, and one for NASA's Artemis mission.
    - Argotec plans to launch its small satellite on board the overall mission. As the host satellite approaches its destination (an asteroid for the DART mission and the moon for Artemis), the Argotec satellite will eject to a distance of about 100m, where it will provide visual inspection of the missions.[36]
- Aviospace
    - Aviospace is working on the CApture and Deorbiting Technologies (CADET) R&D project, with the aim to perform preliminary development of enabling technologies necessary for active debris removal in LEO, including debris recognition by on-orbit spacecraft, autonomous GNC for rendezvous, approach, and capture, and technologies for target capture (Aviospace 2020c).
    - Aviospace has also been involved with other studies of active debris removal, including ESA's e.Deorbit Phase A study (Aviodspace 2020a).
- D-Orbit
    - D-Orbit is in the process of developing a cubesat deployment system, to allow precision orbital insertion of small satellites (Scoles 2017).
    - D-Orbit has partnered with ESA and (now in Chapter 11 bankruptcy) OneWeb to develop a Phase A feasibility study

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[35] Based on Interview(s)

[36] Based on Interview(s)

        - for an active debris removal solution (Spacewatch Global 2019).
    - Politecnico di Milano
        - Politecnico di Milano performs research into active debris removal technologies, and engineers components to enable those efforts (Science Business 2019).
- Key Institutions
    - Italian Space Agency (ASI)
        - ASI was founded in 1988 to fund, regulate, and coordinate space activities in Italy. Its primary activities in OSAM include funding Italian studies to determine what role the country can play in OSAM's development.
    - ArgoTec
        - Argotec is an aerospace engineering company, specializing in small satellites. Their OSAM interests are currently mostly in remote inspection.
    - Aviospace
        - Aviospace is an aerospace engineering company, working to develop debris capture technologies.
    - D-Orbit
        - D-Orbit is a satellite launch and deployment provider (Nyriady 2019; Room 2018), specializing in cubesats and nanosats. The company already offers passive deorbiting technologies, which will directly compete with EOL services (Scoles 2017).
    - Politecnico di Milano
        - Politecnico di Milano performs research to support in-orbit servicing and active debris removal missions.
    - Thales Alenia
        - Thales Alenia is a Franco-Italian aerospace manufacturer. Its activities are discussed in-depth in the France case study.
- Fit with Overall Goals

    - In-orbit servicing, particularly on-orbit satellite repair and large debris removal, has been established as a specific area of focus by the Italian government.

- Investment and Funding
  - Government
    - Exact funding levels of OSAM missions by ASI or the Italian government are unknown.
  - Private
    - Funding levels for OSAM activities is unknown.
- Partnerships
  - Partners and Goals
    - ASI Contributes to Luna-resurs, a partnership between Roscosmos and ESA.
    - D-Orbit has partnered with OneWeb and ESA for Project Sunrise, to develop active debris removal capabilities. Politecnico di Milano is supporting D-Orbit on this project through the development of necessary technologies.
    - Politecnico di Milano cooperates with ESA and D-Orbit to develop components for D-Orbit's ION MK2 spacecraft as a part of ESA's Clean Space initiative for in-orbit servicing and active debris removal (Science Business 2019).
    - Argtotec has partnered with NASA for both the DART and Artemis missions. ASI also financially supports these efforts.[37]
    - Aviospace leads the CApture and Deorbiting Technologies (CADET) project, which is funded by the region of Piedmont of Italy. Aero Sekur will make inflatable equipment, the Blue Group will build software for thermal assessments of debris, DMA will build inertial sensors for attitude estimates, EICAS will contribute star observation systems to support attitude estimates, the Eurix Group will provide 3D reconstructions of targets, SkyTechnology will provide avionics, the Italian Institute of Technology (IIT) will provide sensors for optical recognition, and Politecnico di Torino

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[37] Based on Interview(s)

        - will assist with GNC for non-cooperative rendezvous and solidarization (Aviospace 2020b).
    - Gaps Addressed
        - The Italian government’s guidelines for space and aerospace specifically identify the importance of international relationships. In particular, the government has encouraged ASI and Italian companies to seek partnerships which they can lead using their expertise.
- Drivers
    - National objective: Italy has set in-orbit servicing as a clear objective of its space sector. Having a clearly established national priority for OSAM-related activities will accelerate technological and economic development of the sector.
    - Regulation development: Italy has identified the creation of a regulatory framework as a key factor in driving the space sector, in order to enable commercial space activities. While these regulations have not yet been created, they are now being actively pursued by Italy, which would improve the business climate in the country for companies interested in OSAM.
- Barriers
    - Mars focus: Italy has not yet invested in any lunar missions, and their larger efforts remain focused on robotic missions to Mars. These missions are less likely to require OSAM capabilities, and so even as Italy has established OSAM technology development as an area of focus, there is no major mission pull to drive maturity of the sector.[38]

United Kingdom

- Context: Overall Space Landscape
    - By 2030, the United Kingdom wants to capture 10 percent of the global space economy, up from 5 percent currently. To that end, they have invested in launch companies specializing in small satellites (Sheetz 2018). The United Kingdom sees space as an avenue by which to bolster its economy by supporting private activities from launch to mission end.[39]

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[38] Based on Interview(s)

[39] Based on Interview(s)

    - In addition, the United Kingdom has established a streamlined process for companies to attain regulatory permission to launch and operate commercial satellites.[40] Companies submit a single application for licenses, which is then reviewed by the UKSA, who determine which ministry must authorize the proposed activity. Once the proper licenses have been authorized, if approved, the UKSA provides those licenses to the applicant. Therefore, the applicant interacts with a single source of information, even though different ministries hold licensing authority over different kinds of space activities.
    - The United Kingdom will invest 1.655 billion euros in ESA over the next 5 years, making it the fourth largest contributor to ESA's budget. Those funds will support ESA's required missions, and will also support building the Lunar Gateway, returning the first samples from Mars, building new satellites to analyze climate change, developing an early warning system for solar storms, researching 5G technologies, and removing space debris. The United Kingdom will spend 80 million pounds over the next 5 years on ESA's space safety and security projects, including efforts to understand space weather and to remove space debris (UK Government 2019).
- OSAM Landscape
    - Current and Planned Activities
        - UK Space Agency (UKSA)
            - Specific OSAM missions headed by the UKSA are unknown.
            - The UKSA regulates in-orbit proximity missions (CONFERS 2019), and specifically identified in-space servicing and manufacturing as focus areas in their Corporate Report 2019–2020 (UK Space Agency 2019).
            - The UKSA supports the Luna-Resurs partnership between ESA and Roscosmos to develop lunar ISRU.
            - The UKSA also helps fund ESA's Project Sunrise programme to develop active debris removal capabilities (Henry 2019).
        - Effective Space

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[40] Based on Interview(s)

    - Effective Space wants to provide deorbiting and life extension services to near EOL spacecraft in GEO using small satellites, which it calls Space Drones (Talk Satellite 2019). The Space Drones will use a mechanical arm to grapple the target object, connect via an existing interface, and then relocate the target.[41]
    - It is currently under contractor to serve a commercial operator for two separate missions. These missions were planned to start in 2020, but difficulties with launch opportunities have forced a delay in the program to 2021 or 2022.[42]
- OneWeb (in Chapter 11 bankruptcy discussions)
    - OneWeb views deorbiting of failed or expired satellites as an important consideration, but currently believes most of its constellation will be at a low enough orbit to allow passive deorbiting without the need for servicing.[43]
    - Despite this belief, OneWeb has partnered with ESA for Project Sunrise, to develop active debris removal capabilities (Spacewatch Global 2019).
- The Open University
    - The Open University is in the process of developing the Package for Resource Observation, in-Situ analysis and Prospecting for Exploration Commercial exploitation and Transportation (PROSPECT) in coordination with Leonardo-Finmeccanica to provide drilling and material analysis for the Luna-Resurs partnership between ESA and Roscosmos (Leonardo 2016).
- Satellite Squared
    - Satellite Squared is an early-stage startup developing a deployable solar concentrator, as well as a longer term project called 2Sat to provide contactless power support to a client satellite (Satellite Squared 2020a).

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[41] Based on Interview(s)

[42] Based on Interview(s)

[43] Based on Interview(s)

- Space Forms
    - Space Forms is a startup founded less than a year ago, which is attempting to develop space drones for autonomous inspection and maintenance of satellites (Space Forms 2019).
- SSTL
    - Surrey Satellite Technology Ltd (SSTL) is a small satellite manufacturer, which produced the target satellite for Astroscale's ELSA-d mission, as well as the satellite that will contain ClearSpace's debris capture technology (nets and/or harpoons).[44]
    - SSTL also produced the small satellite for the RemoveDebris mission, a European Commission-funded effort to test debris removal technologies (Surrey Space Centre 2017).
    - SSTL is also currently involved in several mission studies to determine the feasibility of in-orbit assembly of large structures using small satellites (Eckersley et al. 2018).
- The Surrey Space Center at the University of Surrey
    - The Surrey Space Center at the University of Surrey (SSC) is involved with a number of mission studies related to in-orbit assembly and lunar ISRU (Surrey Space Centre 2020b).
    - SSC is also leading the RemoveDebris mission and consortium, funded by the European Commission. SSC is providing coordination, the target cubesats, and a deployable dragsail to deorbit the mission upon completion (Surrey Space Centre 2017).
    - SSC is developing the electromagnetic docking system for the ongoing Autonomous Assembly of a Reconfigurable Space Telecope (AAReST; Underwood et al. 2015).
- The Space Mechatronic Systems Technology Laboratory at the University of Strathclyde

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[44] Based on Interview(s)

- The Space Mechatronic Systems Technology (SMeSTech) Laboratory at the University of Strathclyde assists the Standard Interface for Robotic Manipulation of Payloads in Future Space Missions (SIROM) to develop a standard interface for future servicing missions (University of Strathclyde 2020). SIROM is funded by the European Commission under the Space Robotics Technologies Strategic Research Cluster (SRC) of Horizon 2020 (European Commission 2019c).

- Key Institutions
  - UK Space Agency
    - UKSA regulates UK space activities and facilitates the development of the commercial UK space industry, both by specific grant solicitations and through business development funds for promising startups in more general areas of interest.[45]
  - Effective Space
    - Effective Space was founded in 2013 with the aim of providing deorbiting and life extension services to near EOL spacecraft in GEO using small satellites to provide low-cost services (Talk Satellite 2018).
    - It also has long-term goals to build a fleet of Space Drones in LEO, but first wants to establish its GEO fleet.[46]
    - It is also one of the few companies under contract to provide their service to a commercial operator, with two missions planned.
  - Inmarsat
    - Inmarsat is a satellite telecommunications company, which hosts its constellation in GEO (Inmarsat 2020). While this positions it as a potential target for servicing, and life extension services in particular, it has not yet announced any interest in or official partnership for OSAM.
  - The Open University

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[45] Based on Interview(s)

[46] Based on Interview(s)

    - The Open University is a public research university, working with ESA and Roscosmos, among other partners, on lunar ISRU.
- OneWeb (as discussed above, in Chapter 11 bankruptcy discussions at the time of writing)
    - OneWeb is a global communications satellite in the process of developing its LEO constellation.
- Satellite Squared
    - Satellite Squared is an early-stage startup developing a deployable solar concentrator, as well as a longer term project called 2Sat to provide contactless power support to a client satellite (Satellite Squared 2020a).
    - Its long-term goal is to use the 2Sat technology to facilitate more extensive on-orbit servicing and deorbiting (Satellite Squared 2020b).
- Space Forms
    - Space Forms is an early stage startup developing space drones for autonomous inspection and servicing.
- SSTL
    - SSTL is a small satellite manufacturer headquartered in the United Kingdom and wholly owned by Airbus.[47]
    - SSTL works primarily with commercial customers in order to ensure its projects are economically viable long-term, beyond the timeline of a government-contracted, single-use mission.[48]
- The Surrey Space Center at the University of Surrey
    - SSC performs scientific research into the feasibility of various debris removal, ISRU, and in-orbit assembly technologies. SSC is also involved in a number of ongoing missions, to which it provides smallsats and related technical expertise.

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[47] Based on Interview(s)

[48] Based on Interview(s)

        - The Space Mechatronic Systems Technology Laboratory at the University of Strathclyde
            - The Space Mechatronic Systems Technology Laboratory is working to develop a standardized interface for mechanical connections to enable data, thermal, and power flow between two space objects (European Commission 2019c).
    - Fit with Overall Goals
        - The UKSA's primary focus is on supporting the space economy as a driver of the United Kingdom's overall economy. To that end, it has targeted space robotics as an area of focus. The country has a substantial history researching in-space robotics and automation, and OSAM would capitalize on that expertise.[49]
- Investment and Funding
    - Government
        - The UKSA provided 23.3 million dollars to OneWeb through ESA's Project Sunrise mission to develop active debris removal capabilities (Henry 2019).
        - Funding levels for other OSAM activities are unknown.
    - Private
        - Effective Space is aiming for 100–200 million USD in their next round of funding to enable its Space Drones to provide services. This cost includes the upfront needs of licensing, marketing, sale efforts, the ground segment, and launch.[50]
        - Funding levels for the OSAM activities of other private entities are unknown.
    - Academic
        - The University of Strathclyde received 315,127 euros for its efforts are part of the SIROM consortium through 2019 (European Commission 2019c).
        - The funding levels for the OSAM activities of SSC are unknown.
- Partnerships

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[49] Based on Interview(s)

[50] Based on Interview(s)

- Partners and Goals
    - The UKSA supports the Luna-Resurs partnership between ESA and Roscosmos to develop lunar ISRU capabilities.
    - The United Kingdom's innovation agency, Innovate UK, has funded Astroscale to develop the National In-orbit Servicing Control Centre, to be hosted at the Satellite Applications Catapult, in order to provide the ground segment of in-orbit servicing missions (Weeden et al. 2019).
    - Effective Space licensed its fleet through the UKSA; coordinated its spectrum via Ofcom, United Kingdom's communications regulator; procured its insurance through Marsh We, a UK broker; used the ArianeGroup, GMV, MDA-UK (Geospatial World 2018), and other European entities as suppliers of mission-critical components; tested its technical capabilities at a GMV facility; contracted with IAI to manufacture their small satellite servicers; and has been contracted by a commercial operator for two servicing missions.
    - OneWeb has a public-private partnership with ESA for Project Sunrise, and has subcontracted Japan's Astroscale and Italy's D-Orbit to perform feasibility studies and develop new active debris removal capabilities (Spacewatch Global 2019).
    - The Open University is developing the drilling and material analysis system for use on the Luna-Resurs mission, in coordination with the Italian company Leonardo-Finmeccanica.
    - Space Forms is supported by Catapult and the Westcott Business Incubation Centre, two organizations supported by the UK government to support early-stage business development. The Westcott Business Incubation Centre is also supported by the EU.
    - SSTL built the target for the Astroscale-led ELSA-d mission, which will demonstrate Astroscale's debris capture capabilities, will build the satellite that will host ClearSpace's debris capture technologies, and coordinated with Airbus and the University of Surrey on how to host and deploy net and harpoon debris capture technologies.[51]

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[51] Based on Interview(s)

    - SSTL is in the process of several feasibility studies in partnership with the Surrey Space Center at the University of Surrey (SSC) to analyze potential methods for in-orbit assembly (Eckersley 2018).
    - SSC has partnered with the California Institute of Technology, the Jet Propulsion Laboratory and the Indian Institute of Space Science and Technology for the ongoing Autonomous Assembly of a Reconfigurable Space Telescope (AAReST) mission (Underwood 2015).
    - The SSC coordinates the RemoveDebris mission, which is funded by the European Commission. SSC coordinates the mission and provided target cubesats and the dragsail to deorbit the mission upon completion. Airbus provided the satellite system engineering, harpoon, and net capture technologies. Surrey Satellite Technology Ltd (SSTL) from the United Kingdom provided the small satellite platform and avionics. Innovative Solutions in Space (ISIS) from the Netherlands provided the cubesat dispensers. The Centre Suisse d'Electronique et de Microtechnique (CSEM) from Switzerland and the National Institute for Research in Computer Science and Automation (INRIA) from France, in coordination with Airbus, provided the vision based navigation systems. Stellenbosch University from South Africa also contributed target cubesats for the mission (Surrey Space Centre 2017).
    - The University of Strathclyde is a member of a consortium working on the Standard Interface for Robotic Manipulation of Payloads in Future Space Missions. The other members are Airbus, Thales Alenia, Italy's Leonardo, Germany's German Research Centre for Artificial Intelligence (DFKI), Greece's Teletel, Belgium's Space Applications Services, and Spain's Mag Soar. The consortium is led by Spain's SENER (European Commission 2019c).
- Gaps Addressed
    - The UKSA has extensive partnerships with British commercial entities to provide financial and advisory support while helping guide the nation's OSAM activities.
    - The United Kingdom's commercial and academic entities have international partnerships, to which they bring a more specific area of expertise or hardware. Due to the size of United Kingdom's space companies, no one entity could complete an OSAM project alone, and so international partnerships, particularly those with ESA and

    the European Commission to secure funding, enable activities otherwise infeasible.

- Drivers
    - United Kingdom’s robotic and autonomous systems (RAS) expertise, research infrastructure, and testing facilities position it as a potential leader in OSAM, particularly by providing robotic systems to well-defined missions (UK-RAS Network 2019).
    - The United Kingdom has one of the most streamlined regulatory processes in the world, and has a framework set up for orbital servicing missions. This makes it a uniquely business-friendly environment, particularly for new space companies.[52]
- Barriers
    - Uncertainty surrounding Brexit and how the United Kingdom’s departure from the EU could impact current and future partnerships between UK entities and the European Commission causes some hesitancy among potential partners.[53]

Luxembourg

- Context: Overall Space Landscape
    - The Luxembourg Space Agency (LSA) has no missions for which it solicits grant applications. It responds to the demands of industry and attempts to support and facilitate the expansion of the private space industry in Luxembourg.[54]
    - Luxembourg will provide ESA with 129 million euros over the next 5 years, accounting for 0.9 percent of ESA’s budget (ESA 2019h).
    - Luxembourg is the first European country, and the second worldwide, to establish a legal framework for in-space research utilization. The law, passed in 2017, ensures that private companies that extract resources in space have ownership over those resources and can use them how they see fit. The law does, however, still require Luxembourg companies to be approved for space resources utilization missions prior to launch (LSA 2019g). Luxembourg is planning to develop a law in early 2020 to govern

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[52] Based on Interview(s)

[53] Based on Interview(s)

[54] Based on Interview(s)

all space activities to coordinate and consolidate the legal framework to facilitate commercial use of space (Foust 2019b).

- OSAM Landscape
    - Current and Planned Activities
        - In 2016, Luxembourg announced the Spaceresources.lu initiative to position Luxembourg as a leader in peaceful exploration and sustainable use of space resources.
        - In October 2019, Luxembourg announced its intension to create a Space Resources Research Centre, to be led by the Luxembourg Space Agency, to promote ISRU as a national priority and support scientific research (LSA 2019m).
        - In 2019, LSA announced its intention to establish the European Space Resources Innovation Centre in early 2020, with ESA as a strategic partner, to broaden the scope of the Space Resources Research Centre (LSA 2019a). The Centre focuses on ISRU research and company development. The Centre will facilitate business support and incubation, research, knowledge management, and community management.
        - Blue Horizon is researching bio-ISRU (Brown et al. 2008) with hopes of using microbes to produce compounds critical for life to survive on non-Earth bodies from raw materials found on those bodies (Blue Horizon 2019a; LSA 2019c).
        - Cislundar Industries wants to recycle orbital debris and turn it into valuable raw materials, but is still in the early stages of developing its business case (LSA 2019d).
        - ispace Europe wants to develop the capability to prospect water from the lunar poles and establish standards for in-space mining (LSA 2019e).
        - Kleos currently operates a small constellation of satellites to provide maritime surveillance services, but wants to provide their services with a single satellite using extendable composite booms produced in space (LSA 2019f).
        - Maana Electric is a manufacturer that is researching regolith extraction for use to manufacture solar panels in-space (LSA 2019h).

    - Made in Space Europe is developing a modular, low-cost robotic arm for use on satellite servicing, in-orbit assembly, and ISRU (LSA 2019i).
    - OffWorld is developing robotics for use in the mining and mineral processing sectors, and is currently in the prototyping stage (LSA 2019j).
- Key Institutions
    - Luxembourg Space Agency (LSA) - founded on September 12, 2018 as part of the Ministry of the Economy, the LSA focuses on fostering cooperation between private space companies.
    - The Luxembourg Government helped set up a small venture capital fund to support new space companies, and will be a shareholder of the fund (LSA 2018a).
    - Blue Horizon - owned by OHB SE, a multinational company headquartered in Germany. Blue Horizon wants to create life-sustaining habitats off Earth, and is developing bio-ISRU technologies to produce compounds key to life from raw materials found on non-Earth bodies (Blue Horizon 2019b).
    - Cislunar Industries - startup focusing on ISRU of metals, but still in early stages.[55]
    - ispace Europe - expansion of the Japanese company ispace, which wants to provide commercial transportation to and on the moon. ispace Europe is focused on using those technologies to enable resource extraction from the lunar surface.[56]
    - Kleos - Earth observation company focusing on maritime intelligence. Kleos hopes to assemble extendable composite booms for use on their satellites to facilitate a transition from their current constellation of satellites to a single operational satellite.[57]
    - Maana Electric - solar panel manufacturer attempting to develop means to use lunar regolith to produce solar panels in space.[58]

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[55] Based on Interview(s)

[56] Based on Interview(s)

[57] Based on Interview(s)

[58] Based on Interview(s)

        - Made in Space Europe - established in 2018 in Luxembourg by the American company Made in Space to facilitate the development of modular, low-cost robotic arms.[59]
        - OffWorld - founded in 2016 as a space robotics company, OffWorld is currently prototyping terrestrial mining robots (LSA 2019j).
        - SES - founded in 1985 in coordination with the Luxembourg government, SES has grown to be one of the largest GEO and MEO satellite operators in the world (LSA 2019k). SES had an agreement with Maxar to refuel satellites, but when Maxar dropped out of the DARPA RSGS contract, it cancelled their relationship with SES. As of now, SES has no contractual relationship for OSAM services.[60]
    - Fit with Overall Goals
        - <u>Space Resource Utilization</u> - Luxembourg's national space efforts predominantly seek to use the raw resources of space to facilitate exploration. OSAM technologies are critical to accessing and processing those resources, as well as manipulating the resultant components for use during space missions.
        - <u>Startup Support</u> - LSA seeks primarily to support industrial innovation, and wants to define its own niche to attract space companies and bolster the Luxembourg economy. OSAM companies, and companies developing ISRU technologies especially, are primarily in the early stages of development, making for a natural match with LSA's goals.
- Investment and Funding
    - Government
        - Specific levels of funding for OSAM activities are unknown, but minimal compared with many larger nations. Luxembourg's Fit 4 Start - Space program allows companies to apply for up to 150,000 euros (LSA 2019b).
        - LSA also manages an ESA funding mechanism for ISRU research, but specific numbers are not publicly available.
    - Private

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[59] Based on Interview(s)

[60] Based on Interview(s)

        - OffWorld has 214,000 euros of internal R&D investment (LSA 2019j).
        - Other private entities in Luxembourg have not disclosed their level or sources of funding for their OSAM activities.
- Partnerships
    - Partners and Goals
        - LSA[61]
            - In 2019, LSA announced plans to establish the European Space Resources Innovation Centre in coordination with ESA in early 2020.
            - The Luxembourg Government has signed memoranda of understanding with Poland, Portugal, Japan, China, the Czech Republic, and the United Arab Emirates to exchange information on space resources and promote the adoption of a legal and regulatory framework to facilitate ISRU (LSA 2018b).
            - The Luxembourg Government has also a signed a memorandum of understanding with the U.S. Department of Commerce, while LSA has signed a memorandum of understanding with NASA, in order to support commercial space development in both countries (Foust 2019b).
        - Private Industry
            - Blue Horizon is owned by OHB SE, a German company.
            - ispace Europe is a subsidiary of ispace, a Japanese company.
            - Maana Electric in the Netherlands has offices in the Netherlands (Maana Electric 2019).
            - Made in Space Europe is a subsidiary of Made in Space, an American company.
    - Gaps Addressed
        - LSA
            - LSA's partnership with ESA on the European Space Resources Innovation Centre enables the Centre to provide

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[61] For more on Luxembourg's private sponsors, see LSA 2019l

            greater funding to ISRU companies than LSA alone, and also elevates Luxembourg's role within ESA.[62]
        - LSA's MOUs with other countries seek to promote resource use as an international priority.
    - Private Industry
        - Blue Horizon's ties to OHB SE give it unique opportunities to cooperate with the German space agency, and they are considering establishing a set of offices in Germany (Blue Horizon 2019b).
        - Maana Electric's Dutch offices focus specifically on developing robotic technologies and provide additional technical expertise.

- Drivers
    - Regulatory Framework - Since Luxembourg is just one of two nations in the world to establish a legal framework for ISRU activities, it is one of the few countries that companies can rely on to allow and support their effort to extract and use space resources.[63]
    - Industry Friendly - Luxembourg does not have competitive grants, nor do they have national-level missions for in-space activities. This means LSA works with those companies interested in establishing offices in Luxembourg to ensure that they have unique support through the development and launch process, particular as pertains to understanding the legal framework surrounding ISRU.[64]
- Barriers
    - Funding - LSA lacks the ability to supply substantial financial support for space missions to private companies. This makes it a friendly environment for startups, but LSA alone cannot fund major missions. External funders, which LSA hope would also be commercial players, would be required to enable the financial stability of Luxembourg's commercial space market.[65]
    - International Cooperation - In order to recycle or relocate orbital debris, there is still no framework for dealing with objects of unknown origin or

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[62] Based on Interview(s)

[63] Based on Interview(s)

[64] Based on Interview(s)

[65] Based on Interview(s)

with objects from a nation who does not want their object manipulated by other entities. This has created a problem for several Luxembourg companies that wish to use orbital debris as a potential source of resources in space.

Multinational European Efforts

- Context: Overall Space Landscape
    - The European Space Agency (ESA) is an intergovernmental effort founded in 1973 to coordinate European use and exploration of space (ESA 2019c). ESA has 22 member states and one associate member. Nine countries, including Canada, have cooperation agreements with ESA (ESA 2019i). ESA's total budget for the next 5 years, prior to any funding it may receive from the EU, is 14.4 billion euros (ESA 2019h). As part of its mission after 2019, ESA requested and received an approximately 10 percent increase in funding per year from its member states, to back its refocused emphasis on four pillars: science and exploration, applications, enabling and support, and space safety (Foust 2019a).
    - The European Commission is the legislative initiator of the European Union (EU), and develops and maintains EU policy (European Commission 2019d). The EU, and therefore the Commission, is a supranational entity with 28 member countries (European Union 2019). The EU allocated 12.6 billion euros to cover space activities from 2014 to 2020. For the 2021–2027 period, the Commission has proposed a budget allocation of 16 billion euros, though this proposal is yet to be approved. 9.7 billion euros would be allocated towards its Earth observation systems, Galileo and EGNOS (European Parliamentary Research Service 2019). This proposal is contained within the 100 billion euro proposed research program for the EU, Horizon Europe, which would take effect in 2021 (European Commission 2019a).
    - In 2016, ESA and the EU issued a joint statement declaring their intent to cooperate in improving the use and exploration of space for the development of European society. Specifically, they sought to integrate the space sector into European society and economy, foster a globally competitive European space sector, and ensure European autonomy in accessing and using space (ESA 2019g). The relationship between the two organizations, however, remains complex, as part of the space programme in Horizon 2020 seeks to establish greater independence of the EU's space agency (Boffey 2018).

- OSAM Landscape
    - Current and Planned Activities
        - ESA
            - In 2013, ESA proposed a deorbiting mission called “e.Deorbit” to remove the Envisat Earth-observing satellite, which had failed in 2012. The mission failed to receive sufficient funding, after exploring technologies such as harpoons and nets to capture the failed satellite. In 2018, ESA proposed to change the mission to focus on orbital servicing (ESA 2018). The mission to validate technologies necessary to rendezvous with a decommissioned satellite and remove it from orbit was fully funded in November 2019 (Clark 2019).
            - In 2019, ESA focused on research and development of key technologies for use in OSAM missions, as well as general studies of the technical requirements for a satellite to remove large debris objects from orbit and a study on the feasibility of recycling in space. One in particular is the On-orbit Manufacturing Assembly and Recycling (OMAR) study (ESA 2019e). The OMAR study found that while in-space recycling is still currently technically infeasible and is surrounded by uncertainty over the value it delivers to space missions, on-orbit servicing missions could extend the lifespan of satellites and substantially improve the cost effectiveness of missions when satellites are launched with the expectation that they will be serviced.
            - The Active Debris Removal/In-Orbit Servicing (ADRIOS) mission, announced in 2019, will continue the development of critical rendezvous and capture methods (ESA 2019a).
            - In 2019, ESA commissioned the Swiss company ClearSpace to begin a mission to remove the Vespa upper stage left after an ESA launch in 2013. Launch is targeted for 2025 (ESA 2019a).
            - ESA has partnered with Roscosmos for the Luna-Resurs partnership to develop lunar ISRU, with the Russian-developed lander to arrive at the moon in 2021. The Luna-

    Resurs partnership also receives support from the Italian and UK space agencies (Leonardo 2016).

    - As part of the Luna-Resurs partnership, ESA signed the Italian company Leonardo-Finmeccanica to a contract to develop the Package for Resource Observation, in-Situ analysis and Prospecting for Exploration Commercial exploitation and Transportation (PROSPECT), a system to drill into the Moon's soil and analyze material samples. Leonardo-Finmeccanica has partnered with the Open University, a public research university in the United Kingdom, in order to develop the system.
    - ESA runs Project Sunrise, a public-private partnership between OneWeb and ESA's Advanced Research in Telecommunications Systems programme to develop ADR capabilities (Spacewatch Global 2019).

- EU
    - As part of the Horizon 2020 Space Work Programme 2014, the Commission funded the PERASPERA project to deliver key technologies for space robotics in order to enable new business opportunities in space. PERASPERA is a Programme Support Activity designed to implement a Strategic Research Cluster on space robotic technologies (PERASPERA 2019b). PERASPERA oversees several operational grants provided to research and innovate upon space robotics. The consortium also reviews the state of the art of space robotics, and has conducted two studies on the use cases and operational requirements for in-space robotics for potential future missions (PERAPSERA 2019a). For these studies, research is split into an orbital track and a planetary track, to make specific recommendations by mission type (PERASPERA 2017). The PERASPERA-supporting agencies are the space agencies of France, United Kingdom, Germany, Italy, Spain, and Poland, and the program is coordinated by ESA. DLR has the biggest role in this PSA, and is leading the direction of the program.[66]

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[66] Based on Interview(s)

        PERASPERA provides funding for research studies into the potential for in-space robotics.

        - The delivered key technologies focus on robotics, AI, modularization, standardization, and advanced manufacturing to enable a sustainable, flexible, and economically viable space ecosystem.[67]
        - Through PERASPERA, the Commission funded the development of two interface solutions following the "plug and play" philosophy, aiming to create a standard mechanical interface with supported power, thermal, and data flows (European Commission 2019b; European Commission 2019c).
        - The Commission has now proposed Horizon Europe, a 100 billion euro research and innovation program to succeed Horizon 2020. The main OSAM-relevant efforts include continuation of the PERASPERA roadmap to bolster automation, robotics, AI, and research funding for space surveillance technologies to track and traffic satellites on orbit.[68] The primary aim of the further evolution of PERASPERA is the creation of a sustainable, flexible, and economically viable space ecosystem. Details of Horizon Europe, including funding allocations for specific space programs, have yet to be announced. Specifics are expected to be released in the first quarter of 2020.[69]
        - The Commission also funds a consortium of partners to work on the RemoveDebris mission, launched in 2018, to demonstrate technologies for debris capture and removal (Surrey Space Centre 2017).

- o Key Institutions
    - ▪ <u>ESA</u> is an international entity, which has committed to funding several OSAM missions in late 2019, and supports research and

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[67] Based on Interview(s)

[68] Based on Interview(s)

[69] Based on Interview(s)

    - development of necessary component technologies, including in-space robotics and GNC.[70]
    - <u>The European Commission</u> is a supranational legislative body within the EU whose primary OSAM effort is the PERASPERA consortium to evaluate the feasibility of and support innovation within in-space robotics and cooperative satellite design with the goal of creating new business opportunities in space.[71]
  - Fit with Overall Goals
    - <u>Space for society</u>: Both ESA and the EU view space as a means to bolster the European economy. They view key technologies for OSAM, particularly robotics, as having potential terrestrial applications.[72]
    - <u>Clean Space</u>: ESA has established the “Clean Space” initiative to promote the sustainable use of space, which would likely require OSAM technologies.
- Investment and Funding
  - In 2019, ESA spent about 10 million euros on OSAM-related studies. 1 million went specifically towards in-space manufacturing and recycling. Other funds went either towards research and development of OSAM technologies, or towards feasibility studies for potential applications of OSAM technologies. A 100 million euro mission proposal to revamp the e.Deorbit mission as a multipurpose servicing mission was presented at a ministerial meeting on November 25, 2019, where it was fully funded (Pultarova 2019). In addition, ESA has funded the ClearSpace-1 mission, though exact funding numbers have not been disclosed.
  - The European Commission spent 50 million euros on PERASPERA over 5 years, until 2020 to fund key technology research and development for in-space robotics, including approximately 7.5 million euros for creating standardized interfaces (European Commission 2019b; European Commission 2019c). While the Commission has committed funds to the consortium as part of its Horizon Europe plan going forwards, exact numbers are not yet disclosed.

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[70] Based on Interview(s)

[71] Based on Interview(s)

[72] Based on Interview(s)

- Partnerships
    - Partners and Goals
        - ESA
            - As part of its research and development grants, ESA partners with Airbus, ClearSpace, Avio, GMV, PIA/Made in Space, and a Polish entity.
            - ESA has partnered with Roscosmos for the Luna-Resurs partnership to develop lunar ISRU (Leonardo 2016).
            - ESA has contracted Leonardo-Finmeccanica to develop a drill and material analysis system for the Luna-Resurs partnership. Leonardo-Finmeccanica has partnered with the Open University to develop the system.
            - For Project Sunrise, an effort to develop active debris removal capabilities, ESA has created a public-private partnership with OneWeb, and has brought on several industry contributors, including Japan's Astroscale and Italy's D-Orbit (Spacewatch Global 2019).
        - European Commission
            - PERASPERA is coordinated by ESA, and the partners are the space agencies of France, the United Kingdom, Germany, Italy, Spain, and Poland.
            - The European Commission funds the RemoveDebris consortium to demonstrate debris removal technologies. The Surrey Space Center at the University of Surrey (SSC) coordinates the mission and provided target cubesats and the dragsail to deorbit the mission upon completion. Airbus provided the satellite system engineering, harpoon, and net capture technologies; Surrey Satellite Technology Ltd (SSTL) from the United Kingdom provided the small satellite platform and avionics; Innovative Solutions in Space (ISIS) from the Netherlands provided the cubesat dispensers; the Centre Suisse d'Electronique et de Microtechnique (CSEM) from Switzerland and the National Institute for Research in Computer Science and Automation (INRIA) from France, in coordination with Airbus, provided the vision based navigation systems; and Stellenbosch

        University from South Africa also contributed target cubesats for the mission (Surrey Space Centre 2017).

        - The PERASPERA Standard Interface of Robotic Manipulation (SIROM) project is led by the Spanish company SENER. The other members are the University of Strathclyde in the United Kingdom, Airbus in both the United Kingdom and Germany, Thales Alenia in Italy, Leonardo in Italy, Germany's German Research Centre for Artificial Intelligence (DFKI), Greece's Teletel, Belgium's Space Applications Services, and Spain's Mag Soar (European Commission 2019c).
        - The PERASERPA project MOdular Spacecraft Assembly and Reconfiguration (MOSAR) is led by Belgium's Space Applications Services. The additional members are the German space agency, France's Ellidiss Technologies, Spain's GMV and Mag Soar, Italy's Sitael, the United Kingdom's and France's Thales Alenia, and the United Kingdom's University of Strathclyde (MOSAR 2020).
        - Through the European Operations Framework, PERASPERA coordinates with CONFERS to develop common standards for OSAM applications.[73]
    - Gaps Addressed
        - ESA and the European Commission both maintain the goal of bolstering the European space economy and allowing independence of the European space industry. As such, partnerships are definitional to their mission, in order to use capabilities from across Europe to complete complicated missions that individual countries would be unable to accomplish.[74]
- Drivers
    - <u>Clean Space Initiative</u>: ESA defines Clean Space and sustainable use of space as a cross-cutting technology theme that must be accounted for in proposals for funding from ESA (ESA 2019d).
    - <u>Strategic Research Clusters</u>: The European Commission creates Strategic Research Clusters to coordinate member states and commercial entities

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[73] Based on Interview(s)

[74] Based on Interview(s)

across Europe. This framework enables and pushes rapid advancement in particular areas. OSAM has been elevated to a primary focus through the PERASPERA Strategic Research Cluster, which should accelerate its advancement in Europe.[75]

- Barriers
    - No first mover: ESA views the lack of European governmental customers for OSAM services to be an impeding factor in developing the industry since no entity will handle the upfront costs.[76]
    - No National Security Mandate: Since ESA has no requirement to serve national security interests, and since military applications may provide critical mission pulls to spur the development of OSAM, European nations, and ESA in particular, may be slower to develop OSAM technologies than space agencies that directly support national security interests.

Other

- Context: Overall Space Landscape
    - Several other countries have one or a small number of entities performing work in the realm of OSAM. These are summarized here.
- OSAM Landscape
    - Current and Planned Activities
        - Netherlands
            - The International Association for the Advancement of Space Safety (IAASS) is a non-profit organization established in 2004. Its primary aim is to improve public knowledge of threats to space safety and develop standards for the sustainable use of space, particularly as related to debris (IAASS 2020).
            - The International Space Safety Foundation (ISSF) is a non-profit organization established in the Netherlands, which operates through its Space Safety Institute to establish technical standards for space systems to ensure safety and sustainability (ISSF 2020).

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[75] Based on Interview(s)

[76] Based on Interview(s)

        - Airbus
            - Airbus plans to launch the Bartolomeo platform to the ISS in March 2020. The platform provides plug-and-play capabilities to support payloads from entities that otherwise lack to means of launching and maintain their mission. The same technologies could also be used for on-orbit assembly, a possibility which is of interest to Airbus.[77]
            - Airbus is also developing a set of on-orbit servicing capabilities under the name O.Cubed. Airbus is creating SpaceTugs to perform a variety of missions. Included are life extension, relocation, inspection, and upgrade services for GEO satellites, LEO-to-GEO orbit raising and constellation deployment services, and orbital debris removal (Airbus 2020).
    - Poland
        - Poland's space agency (POLSA) is a member of the PERASPERA consortium as part of the European Commission's robotics Strategic Research Cluster.[78]
    - Spain
        - Spain's space agency (CDTI) is a member of the PERASPERA consortium as part of the European Commission's robotics Strategic Research Cluster.[79]
        - Added Value Solutions
            - Added Value Solutions (AVS) is developing a set of robotic capabilities and mechanical interfaces to support on-orbit servicing missions.[80]
            - AVS recently purchased the American company Advanced Design Consulting to provide additional robotic expertise (Advanced Design Consulting 2020).

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[77] Based on Interview(s)

[78] Based on Interview(s)

[79] Based on Interview(s)

[80] Based on Interview(s)

        - SENER
            - SENER group’s space company is leading the Standard Interface for Robotic Manipulation (SIROM) consortium. SIROM is a European Commission-funded effort to create a standardized mechanical interface for robotic servicing missions that allows for the flow of data, power, and thermal energy (SENER 2019).
    - Switzerland
        - ClearSpace is a private company that will lead the ClearSpace-1 active debris removal mission funded by ESA under the ADRIOS programme. The mission seeks to remove a launch phase from a previous ESA mission (Startupticker 2019).
- Key Institutions
    - Netherlands
        - International Association for the Advancement of Space Safety (IAASS) - non-profit organization established in 2004 to promote public awareness of issues of space safety.
        - International Space Safety Foundation (ISSF) - non-profit organization focusing on the development of technical standards to ensure the safe and sustainable use of space systems.
        - Airbus is a European multinational corporation, headquartered in the Netherlands, with shares traded in Germany, France, and Spain.
    - Poland
        - Poland’s space agency (POLSA) is a member of the PERASPERA consortium as part of the European Commission’s robotics Strategic Research Cluster.[81]
    - Spain

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[81] Based on Interview(s)

            - Spain’s space agency (CDTI) is a member of the PERASPERA consortium as part of the European Commission’s robotics Strategic Research Cluster.[82]
            - Added Value Solutions (AVS) is a technology company with a range of space technology capabilities, including space robotics (AVS 2020).
            - SENER is an engineering and technology group, whose aerospace arm is leading the European Commission-funded Standard Interface for Robotic Manipulation (SIROM) consortium (SENER 2019).
        - Switzerland
            - ClearSpace is a private company founded as an offshoot from the École polytechnique fédérale de Lausanne (EPFL) after several employees and founders worked on the Clean Space One mission for ESA. The company develops active debris removal solutions, including using nets for debris capture (ClearSpace 2020).
- Investment and Funding
    - The SIROM consortium cumulatively received 3,487,442 euros from the European Commission over 5 years, until 2020 (European Commission 2019c).
    - Funding levels for other OSAM missions of the entities discussed here are unknown.
- Partnerships
    - Partners and Goals
        - ISSF and IAASS coordinate extensively to publicize events and promote uniform standards for space safety.
        - The European Commission-funded consortium for SIROM is led by the Spanish company SENER. The other members are the University of Strathclyde in the United Kingdom, Airbus in both the United Kingdom and Germany, Thales Alenia in Italy, Leonardo in Italy, Germany’s German Research Centre for Artificial Intelligence (DFKI), Greece’s Teletel, Belgium’s Space

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[82] Based on Interview(s)

    Applications Services, and Spain’s Mag Soar (European Commission 2019c).

  - PERASPERA is funded by the European Commission, coordinated by ESA, and the partners are the space agencies of France, the United Kingdom, Germany, Italy, Spain, and Poland.[83]
  - ClearSpace is funded by ESA to perform active debris removal as part of the ClearSpace-1 mission.

Asia

Japan

- OSAM Landscape
  - Current and Planned Activities
    - OSAM Activities: Japan is focused on active debris removal (ADR), satellite development, satellite operations, and transportation. Japan sees ADR as one of its national strengths given that they developed rendezvous and docking technology over 20 years ago. Activities are underway both by the government and the private sector.[84]
    - Advantage in ADR: Japan trusts that they will be able to demonstrate debris removal earlier than other countries given that other international government agencies are not as active in ADR. [85]
    - Planned R&D: Completing their goal of being able to grapple and conduct ADR will require more R&D in GNC technology, better AI, funding for licensing of intellectual property, and support from insurance companies.[86]
  - Key Institutions
    - Government: JAXA, Japan’s national space agency, is developing projects and programs focused on on-orbit debris removal, conducting research and development for lunar exploration, and is developing a scenario where servicing and assembly activities can be conducted in the

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[83] Based on Interview(s)

[84] Based on interview(s)

[85] Based on interview(s)

[86] Based on interview(s)

future. JAXA's OSAM activities align with the Japanese government's basic roadmap for space.[87]

    - Private: Astroscale, an orbital debris removal company, is working on technology that would enable active debris removal and end-of-life disposal of satellites. Their large servicer satellite scheduled to launch in mid-2020, ELSA-d, will "test technologies to identify, approach and capture objects in orbit" (Foust 2019). Other Japanese companies also focusing on debris mitigation and lunar ISRU activities, such as ispace, will likely leverage OSAM capabilities.[92]
  - Fit with Overall Goals
    - Environmental Concern: Japanese entities engaged in OSAM are focused on mitigating orbital debris and are motivated to minimize waste, prevent further pollution of the space environment, and improve sustainability.[88]
    - Security: The Japanese view space safety, sustainability and security as related goals and therefore see OSAM as both a national security priority and another reason to improve their ability to monitor debris.[89]
    - Space Exploration: Japan has lunar aspirations and expects that investing in OSAM activities will help them make progress towards lunar exploration.[90]
- Investment and Funding
  - Government
    - The Japanese government will invest $940 million on its R&D program over the next 5 years to help fund space startups, develop its lunar capabilities, and grow its space industry (Nikkei staff writers 2018).[91]
  - Private
    - Astroscale has received investment from private investors and public-private investment funds. To date, they have raised approximately $140M in Series D funding from more than 5 funding organizations.[92]

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[87] Based on interview(s)

[88] Based on interview(s)

[89] Based on interview(s)

[90] Based on interview(s)

[91] Based on interview(s)

[92] Based on interview(s)

- Partnerships
  - Partners and Goals
    - The country's domestic partnerships aim to create space business around servicing while their international partnerships broaden to include human-space exploration, ISS activities, and human-moon exploration.[93]
    - JAXA is currently trying to work with Japanese industry partners to conduct technological demonstrations of on-orbit debris removal. They expect their partnerships will help progress the on-orbit servicing industry.[94]
    - At the moment, JAXA sees few opportunities for partnership with Asian companies because most are concerned with satellite and data application activities rather than OSAM-specific activities. But JAXA welcomes future cooperation with Asian countries.
    - Astroscale currently has partnerships with two European entities. Going forward, they are looking to build ground stations as well as build partnerships with constellation providers and commercial partners. They also prefer partnering with allied entities to avoid any political issues that may arise from OSAM activities (Astroscale 2018).
  - Gaps Addressed
    - Astroscale has established a U.S. presence and is seeking out partnerships in the United States to help them break into the military space marketplace (Hitchens 2019a).
- Drivers
  - Threat of an adverse Event: They see the demand for OSAM being primarily driven by operators’ concern over a future collision or debris damaging their assets.
  - Government Support: The establishment of regulations, support for technological development, funding for the industry, and support for licensing of intellectual property would help accelerate Japanese and global OSAM activities.[95]
- Barriers

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[93] Based on interview(s)

[94] Based on interview(s)

[95] Based on interview(s)

    - Adverse Event: If an adverse event were to occur, the debris/environmental effect could slow down the progression of OSAM activities.
    - Difficulty of OSAM: OSAM requires various technologies and systems. One interviewee stated they do not think one entity could do everything. Several are needed to engage in OSAM.

China

- OSAM Landscape
    - Current and Planned Activities
        - National Goals/Mandates: National documents including the 13th 5-year plan discuss the science and technology innovation 2030 project in which OSAM is included (China Central Government Publishing Site 2016). “The 13th 5 year plan identifies core technology that must be mastered to transform [China] from a major space country to a powerful space country, among the core technology is on-orbit services and service systems that will drive China’s space industry to be ‘more economical’” (China Central Government Publishing Site 2016). China hopes that developments in on-orbit service and maintenance technologies, will “improve the efficiency of space assets in China, and ensure the safe and reliable operation of aircraft on orbit” (Keta Science 2018).
        - White Paper: In their 2016 White Paper on Space Activities, the State Council stated its intention to pursue new space technologies, including on-orbit servicing and maintenance systems (China Central Government Publishing Site 2016). The white paper further explains: “China is to perform experiments on new space technologies to provide solid technological support for its space industry… [China] plans to build in-orbit servicing and maintenance systems for spacecraft and make in-orbit experiments on new theories, technologies and products by tapping various resources” (China Central Government Publishing Site 2016).
        - Megaprojects: Of the 16 Innovation Megaprojects to be fully launched by 2020, one relates to OSAM. “Deep space exploration, on-orbit service and maintenance systems of spacecrafts” (深空探测及空间飞行器在轨服务与维护系统) is a project that will focus on technological breakthroughs in on-orbit servicing to enable more efficient usage of Chinese space assets (Development Solutions Europe 2017; Sciping 2018). The central government has provided funding through the NSFC starting in 2016 for this Megaproject (Natural Science Foundation of China 2017).

- Remote Observation: In 2008, China released BX-1, a satellite equipped with optical cameras for the stated purpose of performing an inspection demonstration of the Shenzhou-7 orbital module. There was concern that BX-1 was a test for co-orbital anti-satellite (ASAT) attack capabilities against the ISS, but the movements and behaviors of BX-1 do not support these concerns (Weeden 2008).
- Rendezvous: Since 2010, China has built experimental satellites to test maneuvering and grasping capabilities; they have also built satellites to conduct proximity maneuvers. One of these satellites, SY-7, carried a smaller companion satellite that it released in orbit and may have been equipped with a robotic arm to assist in on-orbit inspection (Weeden 2010; Weeden 2019a). From 2016 to 2018, China launched satellites that conducted rendezvous and proximity operations (RPOs) with other previously launched Chinese satellites. In 2016, China also launched Aolong-1, a solo satellite that simulated debris removal with its attached robotic arm (Roberts 2019; Secure World Foundation 2018). One source remarked that only a small sample of Chinese RPO activity demonstrates rendezvous capability on levels comparable to those of the United States (Weeden 2019b).
- Refueling: China has conducted two major demonstrations within the area of refueling, the first to refuel a satellite, Tianyuan-1, and the second to refuel a spacecraft, an operation in 2017 between China's Tianzhou-1 spacecraft and their second experimental space station, Tiangong-2. (Xinhua 2016a; Xinhua 2017; UNOOSA 2018). Both demonstrations have been accompanied by research into supporting technologies for more complex missions including a) long-term on-orbit storage of fuel, and b) refueling missions that involve multiple satellites and trajectories (Zhang S., Xu, and Wei 2018; Zhang X. 2018; Yu, Liu and Hao 2018).
- Repair and Replace: Many of China's satellite operations provoke discussion about China's potential development of on-orbit satellite repair abilities, but China has not performed any demonstrations of on-orbit satellite repair or replacement or upgrade of parts (Space China 2015).
- Assembly: China's new station, the Tiangong Space Station, scheduled to launch in 2020 will be the first large Chinese demonstration of on-orbit assembly technologies in practice (Xinhua 2019). The station is scheduled to be assembled on orbit by 2022 and is equipped with multi-purpose robotic arms to assist with assembly, docking, maintenance and

    replacement (UNOOSA 2018). These capabilities allow for complete on-orbit assembly of the station without humans present (NASA 1999). The Chinese space station will be significantly smaller than the ISS at an expected mass of 66 tons alone or up to 100 tons when docked with other spaceships and vehicles, significantly less than the current ISS's 450 tons (UNOOSA 2018). Chinese researchers have begun mission planning and studying constraints surrounding on-orbit assembly for space based solar power stations and large-aperture space telescopes (Cheng et al. 2016; Wang et al. 2018; Xu n.d.).

  - <u>Manufacturing:</u> Although manufacturing is China's least mature OSAM area, China has conducted two demonstrations of on-orbit manufacturing capabilities utilizing 3D printing. In 2016, China conducted their first microgravity 3D printing experiment using various composite materials (Chinese Academy of Sciences 2016). In 2018, China then 3D printed ceramic molds in microgravity and used those molds to test a microgravity metal casting technique (Xinhua 2018). Although these demonstrations were relatively advanced in the context of worldwide OSAM capabilities, with only a few other on-orbit 3D printing demonstrations and the ceramic printer being the first of its kind, they are far from being ready for use in a practical on-orbit setting.

- Key Funding Mechanisms and Institutions
  - Research Funding Mechanisms
    - Natural Science Foundation of China**:** The National Natural Science Foundation of China (NSFC) has identified spacecraft control for capture of rolling targets as a major project (Natural Science Foundation of China 2016). NSFC funds basic and applied research through its various science and technology grants (Natural Science Foundation of China n.d.). NSFC has funded research in the following areas of interest to OSAM: On-orbit assembly for MR-SPS (Multi-Rotary Joints SPS) missions (Wang et al. 2018); simulated on-orbit capture of tumbling uncooperative target satellites, demonstrating approach, flying-around, capture and release of continuous rotational objects (Shenyang Automation Research Institute 2017; Xie et al. 2018); SPS vibration suppression systems for on-orbit assembly and operation (Wang et al. 2019); and self-calibration strategies to increase docking capabilities (Wu et al. 2018).

  - High-level Talent Innovation Support Program or the Ten-Thousand Talents Program: The Ten-Thousand Talents Program is funded by the Central Leading Group for Coordinating Talent Work under the Chinese Communist Party’s Central Commission’s (CCPCC) Organization Department, the Central Propaganda Department, the Ministry of Human Resources and Social Affairs, the Ministry of Education, and the Ministry of Science and Technology (Sheng 2013). The High-level Talent Innovation Support Program funds critical innovations within OSAM, such as assembly sequence planning of SPS modules (Wang et al. 2018).
  - Program 973 or the National Key Research and Development Plan: The National Key Research and Development Plan is supported by the Ministry of Science and Technology in coordination with project specific government entities to implement national key research and development objectives (Ministry of Science and Technology 2017; China Innovation Funding 2017; Nankai University Science and Technology Research Department n.d.). Within OSAM, funding has gone towards research on self-calibration strategies to increase docking capabilities and simulated on-orbit capture of tumbling uncooperative target satellite (Shenyang Automation Research Institute 2017; Xie et al. 2018; Wang et al. 2019).
  - Fundamental Research Funds for the Central Universities of China: The Central Universities of China are the top Chinese universities analogous with the Ivy League in the United States. The Fundamental Research Funds for the Central Universities of China promotes research from these institutions. Among other research, this funding has contributed to OSAM research within these institutions (Wang et al. 2019; Wang et al. 2018).
  - Fund for Advanced Research Projects in Manned Space: The Fund for Advanced Research Projects in Manned Space has sponsored analysis of challenges in on-orbit servicing technology, reviewing spacecraft autonomous learning theories (Xie et al. 2019).
- Institutional Actors
  - CASC: The Chinese OSAM landscape is dominated by the China Aerospace Science and Technology Corporation (CASC), the state-owned corporation and main contractor for the Chinese space program (Chinese Academy of Sciences 2018). Within CASC, at

least 5 institutions are conducting research with OSAM implications.

i. Shanghai Academy of Spaceflight Technology: The Shanghai Academy of Spaceflight Technology (SAST) is one of China's primary launch and spaceflight technology facilities (China Aerospace Science and Technology Corporation 805 Research Institute 2014). SAST has multiple research institutes involved in OSAM activities. The 805th Research Institute, also known as the Shanghai Aerospace System Engineering Institute, completed full-scale ground testing of on-orbit service in China, simulating close approach, docking, robotic arm module replacement and propellant replenishment (China Aerospace News 2015). Researchers at the 805th institute have also been involved in steps to increase the maturity of OSAM technology and assembly techniques (Zeng et al. 2018). The Shanghai Academy of Spaceflight Technology (through contract with CASC) built Shi Jian-12 and the SJ-06F, conducting close approach and co-orbital ASAT capabilities. No scientific research has been published on either satellite, leading researchers to hypothesize the satellites are being used for electronic intelligence but, as mentioned above, the movements and behaviors of BX-1 do not support these concerns (Weeden 2008). Researchers from the Shanghai Electro-Mechanical Engineering Institute (also a part of SAST) have been involved in OSAM related research such as a self-calibration strategy to increase docking capabilities (Wang et. al. 2019).

ii. Qian Xuesen Laboratory of Space Technology, CAST: Qian Xuesen Laboratory of Space Technology is one of CAST's "special innovation zones" (Qian Xuesen Laboratory 2019). While the lab has not published documents with OSAM implications, Qian Xuesen Laboratory researchers have published journal articles on topics of assembly sequence planning of SPS and the on orbit assembly sequence of the MR-SPS (Wang et al. 2018).

    iii. CALT: CALT researchers have studied ways to increase cryogenic storage for in orbit vehicles (Zhang et al. 2018), but to our knowledge CALT is not pursuing other activities in OSAM.

    iv. CAST's Beijing Institute of Control Engineering and National Key Laboratory for Space Intelligent Control Technology: Researchers at the Beijing Institute of Control Engineering and the National Key Laboratory for Space Intelligent Control Technology have published studies reviewing foreign technology development within OSAM (Xie et al. 2019).

- CAS: There is support for OSAM within the Chinese Academy of Sciences (CAS) (Science and Technology Daily 2019). Within CAS, STPI has identified two labs working on OSAM capabilities:

    i. Technology and Engineering Center for Space Utilization, Key Laboratory of Space Utilization (Shu 2018; Zhang et al. 2018): Researchers from the Key Laboratory of Space Utilization at the Chinese Academy of Sciences developed nano-scale solid ceramic paste materials that can be used for high temperature 3D printing for China's Space station and other OSAM tasks (Shu 2018).

    ii. Space Automation Technology Laboratory at the Shenyang Institute of Automation: Researchers from the Space Automation Technology Laboratory at the Shenyang Institute of Automation are engaged in simulated on-orbit capture of tumbling uncooperative target satellite (Shenyang Automation Research Institute 2017; Xie et al. 2018) and research on docking mechanisms for on orbit maintenance (Li 2018).

- Universities: STPI has identified the several universities that support Chinese OSAM technology research and development, including: State Key Laboratory of Structural Analysis for Industrial Equipment at Dalian University of Technology (Wang et al. 2018; Wang et al. 2019); College of Aerospace Engineering at Shenyang Aerospace University (Wang et al. 2018); and Beijing Institute of Technology (Zhang et al. 2018).

        - Private: The Chinese company i-Space, which lists on-orbit servicing and high-value upgrades as one of its products and services, was responsible for China's first successful rocket launch by a private Chinese company in 2019 (i-Space 2019a).
        - CASIC: The Chinese Aerospace Science and Industry Corporation (CASIC), conducts major research activities and operates a network of research institutions, centers, and universities. This study has not been able to identify specific examples of CASIC engagement in OSAM activities. Because of CASIC's role in China's defense base, CASIC's OSAM activities may not be publicly documented.
    - Fit with Overall Goals

      Strategic Plan:

      China considers its space program to be an essential part of its three-step strategic development plan. It also aims to be at the forefront of innovative countries by 2030 and a world science and technology power by 2050 (Xinhua 2016b).

      Space exploration and science are meant to promote scientific progress as well as meet economic, national security, and social progress demands. With these purposes in mind, China has chosen to grow its space program with the vision of building the country into "a space power in all respects" (State Council Information Office 2016).

      <u>Economy</u>: Chinese leadership regards on-orbit servicing and maintenance as a core technology that must be mastered for their space plan to succeed. They understand that realizing on-orbit servicing and maintenance goals will make China's space industry economically efficient and feasible (Xiong 2016).
    - Investment and Funding
        - n/a
- Partnerships
    - Partners

      <u>Russia:</u> Russia supported early and preliminary work on the new Chinese space station through technological exchanges on docking mechanism development options around 2000, which was followed by independent Chinese design, manufacturing, and testing (Xinhua 2011).

      <u>United Kingdom</u>: The Changchun Institute of Optics, Fine Mechanics and Physics (CIOMP), operated by CAS, has developed a collaborative relationship with the University of Surry in the United Kingdom around intelligent space manufacturing technology. This relationship and a later MOU led to the 2017 announcement of the Ultra-Large Aperture On-Orbit Assembly Project, a project that would be jointly led by the two institutions (Changchun Institute of Optics, Fine Mechanics and Physics, 2017). There have been no public updates from either institution on the

    - project since 2017, but both continue to independently publish related research on on-orbit telescope assembly.
  - Gaps Addressed
    - n/a
- Drivers
  - n/a

India

- OSAM Landscape
  - Current and Planned Activities
    - <u>India's Space Activities:</u> India is working on improving the design and development of satellites to meet their growing communications, Earth observation, navigation, meteorology, and space science needs. Beyond the capabilities of their satellites, they are primarily concerned with developing their launch capabilities for both commercial and geopolitical purposes (Indian Space Research Organization 2017). India has a thriving space program and is considering a crewed space station in low Earth orbit in addition to robotic missions to the Moon and Mars.
    - <u>OSAM Activities:</u> India intends to conduct a space docking experiment in 2020. ISRO chairman Dr. K Sivan stated, "We are going to conduct a docking experiment…in which two experimental modules will be sent from space and the two will be made to dock with each other" (Singh 2019). It is unclear what other OSAM activities India is engaged in or developing. We reached out to ISRO for details and did not receive a response.
  - Key Institutions
    - <u>Government</u>: ISRO, the Indian Space Research Organization, is India's national space agency. Sustained investment in the aerospace sector by the government has allowed India to rapidly develop their space capabilities (Nguyen 2019). India's space program has also been guided by the government's Department of Space, which has developed policies broadly under satellite communication and remote sensing (Anilkumar and Singai 2020).
    - <u>Private sector:</u> India is developing a commercial space sector, but for the moment, it is quite nascent.
  - Fit with Overall Goals

        - India’s interest in conducting a docking experiment in 2020 aligns with their goal to set up the country’s “own space station and sending humans to that station” (Indian Space Research Organization 2017).
- Investment and Funding
    - Government
        - n/a
    - Private
        - n/a
- Partnerships
    - Partners and Goals
        - <u>Partnerships with U.S. entities:</u> India is interested in reaching out to the United States to promote industry to industry cooperation, especially with U.S. entities on the West Coast.
        - <u>International Partnerships:</u> Though it is unclear which partnerships India is a part of relate to OSAM, they currently collaborate with 50+ countries on space activities (Sivan 2019).
    - Gaps Addressed
        - n/a
- Drivers
    - <u>Education:</u> A search through IAC papers demonstrated that Indian academics at local universities such as Lovely Professional University and SRM Institute of Science and Technology are developing literature relevant to OSAM and/or are collaborating internationally with academics on OSAM research.
    - <u>Heritage:</u> In addition to the expertise India has available, India’s engineering heritage, achievements in launch, and exploration “lay the foundation for space startups to emerge” (Henry 2019b).
- Barriers
    - <u>Lack of a National Policy:</u> India has conducted space activities since 1960 without a national space policy. However, the development of a national space policy, the 2017 Space Activities Bill, is now under consideration by its parliament to encourage the participation of Indian industry and startups. The policy would also establish a licensing regime that would oversee the performance and activities of private companies (Prasad 2019). In a public

discussion between U.S. and Indian government officials, the lack of a policy was highlighted as barrier that has kept small businesses from being more involved in Indian space activities.

Singapore

- Context: Overall Space Landscape
  - Singapore's Space Economy: In 2013, Singapore established a National Space Office to help "grow a competitive space industry." Since 2011, Singapore has launched 13 small satellites and more than 13 startups from across the satellite value chain have emerged (Economic Development Board 2020; OSTIn Brochure 2020).
- OSAM Landscape
  - Current and Planned Activities
    - OSAM Activities: Singapore is not very active in OSAM. One interviewee stated that though they believe OSAM will not be neglected, the market is not big enough for them to get involved directly.[96]
  - Key Institutions
    - Universities: While Singapore is not working on OSAM specifically, Nanyang Technological University is active in Singapore's space initiatives.
    - Private: One company wants to work on life extension services for satellites where they would design a servicer specific to the customer.[97]
  - Fit with Overall Goals
    - Leadership: Singapore wants to be considered a leader where entities and businesses working on space and OSAM can converge from across the world to engage in valuable conversations and share knowledge. They also see being the global hub as a way to access developments in technology.
- Investment and Funding
  - Government
    - No discernable funding.
  - Private

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[96] Based on interview(s)

[97] Based on interview(s)

    - One company we interviewed was pre-revenue and had received more than $250k in funding, but would need $15–20 million to conduct OSAM activities in the coming years.

- Partnerships
  - Partners and Goals
    - <u>Existing Partners:</u>
    - Has a relationship with Astroscale, a Japanese entity working on debris removal.
    - Has partnered with India on launch activities.
    - Has a relationship with OneWeb and SSTL in the United Kingdom.
  - <u>Future Partners:</u> While Singapore finds it easier to work with their existing relationships, the prospect of future partnerships would depend on the ability to structure a mutually beneficial deal. They do not have a position on whether they would partner with China on OSAM. China has not been a traditional partner of Singapore in space developments, so collaboration in OSAM may not be easy.
- Drivers
  - <u>Business environment:</u> The growth of Asia's space market can be attributed to the perception of a friendly business environment that offers businesses greater flexibility.
  - <u>Cheaper Technology:</u> Space technology becoming cheaper in the past decade has provided small players and startups greater access to the industry and has contributed to the growth of Singapore's space industry over the past 6 years (Teo 2018).
- Barriers
  - Singapore is a small country and may not have the critical mass to play a driving role in OSAM developments. However, it is interested in the industry and will work on identifying suitable opportunities where they can play a role.

Rest of the World

Russia

- Context: Overall Space Landscape

  - Russia has been regularly working with the United States on civil space missions since shortly after the collapse of the Soviet Union, though it has been less cooperative with other space systems and has interfered with U.S. military space operations.
  - Falling oil prices and a shrinking national economy have reduced Russia's space program budgets. Its budget has fluctuated from 2013's high of $9.75 billion to 2018's $4.2 billion (Seminari 2019).
  - In 2016, Russia released its 10-year space strategy, calling for increasing its telecommunications capacity, replenishing its aging Earth observation systems, streamlining its launch fleet, and maintaining GLONASS (Zak 2016b). A 10-year budget of $20.4 billion was approved in 2016, far short of the $56.4 billion proposed in 2014.
  - In 2013, after the failure of a Proton-M launch vehicle, Russia took drastic steps to reorganize its space industry. The United Rocket and Space Corporation, a joint-stock corporation, was formed by the government to consolidate the sector. In 2016, the state agency was dissolved and the Roscosmos brand was transferred to this corporation (Dickerson 2015).
  - Russia conducts science research on the ISS and is planning other planetary science missions for the 2020s, including a lunar orbiter with ground penetrators and another Venus lander.
  - Burevestnik is a co-orbital ASAT program that may be supported by Nivelir, a surveillance and tracking program. The applications of these programs could include surveillance and the inspection of foreign satelllites. The testing conducted thus far does not conclusively indicate that they are for an ASAT program, although the high-velocity deployment of sub-satellites appears to allow for aggressive applications. Burevestnik also includes ground-based infrastructure at the Plestesk Cosmodrome near Noginsk-9, which was formerly the ground-control center for Soviet co-orbital ASAT programs. Nivelir's inspection satellites may support Burevestnik by either testing RPO technologies or providing tracking and targeting support. Some research suggests Burevestnik may utilize low-temperature sold-fuel generators to defend spacecraft from attacks, as the aersols would create a mask and damage potential assailants, as well as disable certain systems.
- OSAM Landscape
  - Current and Planned Activities
    - Cosmos-2519
      - In 2017, Izvestia reported that the Ministry of Defense successfully tested a servicing satellite for R1: Remote Inspection, called the maneuvering military satellite inspector (маневрирующий военный спутник-инспектор). This satellite is capable of approaching other

orbiting vehicles and inspecting them (Valchenko et al. 2017).

        - “According to domestic experts, maneuvering satellite inspectors will become an important element of the Russian orbital grouping, they will play the role of a deterrence tool in the space military race.”
        - The tests in 2017 confirmed their ability to automatically undock the satellite from its platform, remotely control its flight, use on-board equipment, and transmit the received surveillance data to the ground.
        - This satellite was launched from platform Cosmos-2519.
    - Cosmos-2519 was constructed by the NPO Lavochkin design bureau.
- Cosmos-2535, -2536, -2491, -2499 (Terehov 2014), -2504, -2519
    - According to Rambler, “Russian inspector satellites are built on the basis of the Karat-200 and Navigator platforms, which can be adapted to monitor satellites in geostationary orbit” (Anpilogoy 2019).
        - Inspector satellites built on Navigator largely correspond to the parameters of the U.S.’s PAN satellite, which is based on Lockheed Martin’s A2100 satellite bus.
        - Cosmos-2535 and Cosmos-2536 would more likely resemble Karat-200, the lighter platform, and would likely resemble GSSAP satellites.
    - Cosmos-2491, -2499, -2504, and -2542 in particular startled the global community with erratic movements near other satellites.
        - In February 2020, concerns over Cosmos-2542 gained significant press coverage.
            - Cosmos-2542 split into two separate satellites—Cosmos-2542 and 2543—when it entered Earth orbit in the same plane as USA 245, a National Reconnaissance Office (NRO) satellite (Adamczyk 2020).
            - Publicly, the Russian Ministry of Defense stated this satellite was intended to perform an experiment “to continue work on assessing the technical condition of

      domestic satellites" (Russian News Agency Tass 2019).
      - On January 20, Cosmos-2542 and Cosmos-2543 came within 160 km of USA 245/ KH-11 (Adamczyk 2020).
      - Cosmos-2542's relative orbit to USA245/ KH-11 was such that it observed one side of the NRO satellite when they first entered sunlight, and migrates to the other side by the time they enter the eclipse (Hennigan 2020).
      - Brian Weeden of Secure World Foundation has reported Cosmos-2542's position could allow it to determine where USA 245/KH-11 is "pointed" (Hennigan 2020).
    - Jonathan McDowell, an astronomer from the Harvard Smithsonian Center for Astrophysics, reported that Cosmos-2491 "may have broken apart in space based on data collected by the US Air Force" (Monzon 2020).
      - The Air Force identified 10 fragments from Cosmos-2491 in LEO.
- Nivelir is the project under which Cosmos-2491, 2499, and 2504 were built.
  - Nivelir ("Dumpy Level") or 14K167 began as a project in 2011. The Central Scientific Research Institute of Chemistry and Mechanics (CNIIHM or ЦНИИХМ) was awarded a grant by the State Scientific and Technical Center Garant (GNTTs Garant), which belongs to the Ministry of Economic Development.
    - Most Russian military space satellites begin with a Ministry of Defense contract, usually awarded to Roscosmos. Nivelir, therefore, is abnormal.
  - Nivelir is a project to build small satellites to inspect other satellites in space (Hendrickx 2019).
- Burevestnik ("Stormy Petrel" or 14K168) is another CNIIHM top-secret space project.
  - This project began in September 2011.
- Luch Series
  - Luch/Olympus is located in geostationary orbit and is suspected to be a spy satellite capable of conducting R1: Remote Inspection and SIGINT operations.

      - Todd Harrison, the director of the Aerospace Security Project of the Center for Strategic & International Studies, states that Luch is likely a tool for inspection and data collection on other satellites (Interfax Ukraine 2019).
    - In April 2015, Luch/Olymp-K maneuvered within 10 km of Intelsat 901 and the nearby Intelsat 7 (Gruss 2015).
    - In 2017, Luch-4 was suspected of maneuvering closely to the French satellite Athena-Fidus, used for secure military communications (Leicester et al. 2018).
    - Luch/Olympus was built for the Russian Ministry of Defense.
  - Strela (Стрела)
    - The Strela (in Russian, Boom or Jib) cranes are four Russian built cargo cranes on the Russian Orbital Segment of the International Space Station.
      - Strela was originally designed for the Russian Space Station Mir (Ckorenko 2016).
      - Their design is fundamentally different from segment manipulators, such as the Canadarm 2 or European Robotic Arm (ERA), and is a 15 meter telescopic structure. As such, Strela can contract and rotate, but has fewer degrees of freedom than ERA or Canadarm 2.
    - For Buran, another robotic manipulator was developed and tested successfully, but was never launched (Technover.Ru 2018). This system Stork (Аист) was developed at the State Scientific Center- the Central Research and Development Institute of Robotics and Technical Cybernetics (SSC CRI RTK RF) (Ckorenko 2016).
      - Stork’s total length was 15 meters. The manipulator operated in three planes and had six rotational degrees of freedom. Stork could be controlled from within the spacecraft, as well as from Earth (Encyclopedia of Winged Space n.d.).
- Key Institutions
  - Roscosmos
    - In August 2019, Izvestia reported that Roscosmos State Corporation has “patented a method for masking satellites,” making their operations significantly harder to detect from the ground.

    - This is achieved with a coating of “light scattering special bubble film” (рассеивающей свет специалной воздушно- пузырчатой пленки).
    - This technology will decrease the visibility of an object from earth by 10 or more times (Izvestia 2019). This will be used to mask spacecraft at a height of more than 10,000–20,000 km, where radar-based surveillance tools become ineffective.
    - In addition to applications of stealth, it could cause issues with space traffic management if the objects cannot be tracked relative to other satellites.
- RSC Energia
  - RSC Energia has conducted a practical experiment for transmitting power between satellites or from the ground to satellites (“transmission of electricity in the atmosphere” – [провела практический эксперимент по передаче электричества в атмосфере]) in efforts to develop “orbital gas stations” (Litovkin 2019) to conduct R6: Recharging operations.
    - The ability to beam power to satellites means they can be designed with smaller batteries and solar panels, as power can be delivered during peak needs, and during orbital eclipse. This would drastically change a satellite’s normal concept of operations while simultaneously providing key dual-use capabilities.
    - It seems that RSC Energia is also attempting to develop some orbital refueling capabilities, but this work is only mentioned in passing in articles about A.F. Mozhaysky Military-Space Academy’s work.
  - RSC Energia partnered with Tomsky Polytechnic University to create the first Russian nanosatellite (Tomsk-TPU-120), which was 3D printed on the ground. They are also collaborating to send a 3D printer to the ISS in order to print additional satellites on orbit. They intend to initially use polymers as printing material, before moving onto reinforced materials. A prototype will be ready in 2020.
  - RSC Energia is partnering with Airbus Defence and Space (Airbus DS) to develop a space tug for commercial communications satellites. This tug capability will be used to move commercial communications satellites to geostationary orbit. Airbus DS and RSC Energia think this

        could also be used as a “space tanker and space garbage collector.” (Sputnik News 2016)

- 3-D Bioprinting Solutions (Main Investor is INVITRO)
    - Mission organaut (also stylized Organ.Aut)
        - Organaut is a Russian biomedical 3D printer that was delivered to the ISS in October 2018 and is intended to last 5 years. Crew Commander Oleg Kononenko was the cosmonaut initially responsible for this experiment. The 3D Printer was developed by 3D Bioprinting Solutions, which was founded by INVITRO, the largest private medical company in Russia (Baklanov 2018).
        - Orgonaut is the world’s first magnetic bioprinting experiment in orbit (Roscosmos et al. 2018). They intend to print the cartilage and thyroid glands of a mouse as a test (Lapik 2018).
- NPO Lavochkin
    - NPO Lavochkin is a state-owned company that manufactures and develops spacecraft, satellites, and interplanetary probes.
- Tomsk Polytechnic University
    - In 2017, Tomsk Polytechnic University launched the first Russian nanosatellite (Tomsk-TPU-120), which was created with a 3D printer (Syintsova 2017). This project was done in conjunction with RSC Energia. Chief Specialist Sergey Nikolaevich Samburov of RSC Energia supervised this project (Southwestern State University n.d.).
        - As of April 2019, this project will be continued under the consortium “Space Information Systems and Technology,” which will also include scientists from Tomsk State University and Tomsk State University of Control Systems and Radioelectronics RiaTomsk 2019). This consortium will continue to 3D print satellites.
    - RSC Energia and Tomsk are also collaborating to send a 3D printer to the ISS. They intend to initially use polymers as printing material, before moving onto reinforced materials. A prototype will be ready in 2020.
- A.F. Mozhaysky Military-Space Academy
    - A.F. Mozhaysky Military Space Academy is the largest polytechnic university of the Ministry of Defense. Their project “Space Gas Station” (“Космической

Бензоклонки”) intends to launch several dozen refueling satellites (“робот-заправщик”) for R6 – Recharge operations.

- - - - - Their prototype has solar panels, photovoltaic modules, and a pulse-based supercapacitor.
        - This project has been submitted for consideration by the Main Directorate of Research and Technology Support of the Advanced Technologies of the Ministry of Defense. Colonel Dmitry Kargu is the lead on this project at A.F. Mozhaysky.
          - Quote from Izvestia article: “Our idea allows us to increase the power supply of satellites located in the shadow portion of the orbit, where there is no sunlight, as well as in situations where the supply of electricity is not enough to perform the target tasks. That is, in fact, to prevent the loss of the device” (Litovkin 2019).
        - Izvestia reports this is to maintain the operations of Cospas-Sarsat, a treaty-based international satellite search and rescue program.
          - There are nine GEO satellites in this network. It is unclear if other international partners approve of such missions.
    - Ministry of Defense
      - The Cosmos satellites are operated by the Ministry of Defense.
      - The A.F. Mozhaysky Military Space Academy’s “orbital gas station” was submitted to the Ministry of Defense for approval.
      - All of the Kosmos satellites and Luch were built by and for the Russian Ministry of Defense.
  - Fit with Overall Goals
- Investment and Funding
  - Government
  - Private
    - Russia has very little private space investment compared to the U.S. and other western countries.
    - In 2016, Roscosmos said it would allow private companies access to the space services market, but not before 2020 (Collinson 2016). Dmitry Rogozin, Director of Roscosmos said this publicly in 2016 and that this would be reflected in a report to President Putin.

            - Again in 2018, Rogozin publicly claimed that private investment would be key for national space efforts.
            - The Moscow based Center for Strategic Assessments and Forecasts reports that the business and legal environments for space startups are highly unfavorable (Center for Strategic Assessment and Forecasts 2017).
        - In 2010, President Medvedev launched the Skolkovo Innovation Center, and space and telecommunications was one of the five core clusters of this plan. “As of October 2016, there were more than 180 participants in Skolkovo in various technological domains related to space activities. Skolkovo allows these participants to find investment, partners, and clients on world markets” (McClintock 2017).
            - There have been “modest victories” of this effort: Dauria Aerospace, smallsats; SPUTNIX, ground equipment and testing for smallsats; Spactralaser, laser ignition modules for Soyuz engines; Kosmokurs, suborbital launch vehicle for tourism; and Lin Industrial, light launch vehicles for smallsats. Dauria by far has the most capital—as of 2013, they received $20 million in Series B funding in 2013 from 12BF Global Ventures (NY) (Rapoza 2016).
            - In their 2019 Annual Report, Skolkovo reported the following statistics for their Advanced Production Technologies, Nuclear, and Space Technologies Cluster (Skolkovo Innovation Center 2019):
                - 394 Participants
                - 8.536 billion RUB in revenue (~$134 million)
                - 2.71 billion RUB in investments (~$42 million)
- Partnerships
    - Partners and Goals
    - Gaps Addressed
- Drivers
    - In all of the projects addressed above, competition with the United States is a significant driver. The capabilities of the United States are almost always compared to those of Russia.
        - Many of the technologies Russia is developing that fall under OSAM have more direct pathways for dual-use operations or less-than-practical peaceful applications compared to most of the other programs that are discussed in this report.
        - Most of the technologies that fit this description could be used to counter or disrupt U.S. military satellite operations and capabilities.

        - Since military operations are primarily driving the domestic Russian space program, they are not limited by market forces to develop technologies and capabilities for specific applications that may not be profitable or useful in the short term, though they could have long-term strategic value in a space conflict.
- Barriers
    - Russia’s space infrastructure and workforce are aging. The frequency of launch failures on the Soyuz rocket could grow, limiting progress in all Russian space technology development. A lack of private or civil applications for OSAM could force military mindsets that limit creative thinking and technology transfer between applications that could speed progress in multiple areas.
        - Existing system reliability in Russian space is declining over time (Zak 2016a; Bodner 2017).
        - Aging of workforce without young professionals to replace them (McClintock 2017).
    - Lack of private capital means applications in OSAM technologies and capabilities may not evolve or disseminate into other applications and markets.
    - Post-2020, this may change, but other countries have already embraced commercial space and are further ahead than Russia, so it could be another decade before Russian commercial space is caught up with others.

Canada

- Context: Overall Space Landscape
    - Canada has been a leader in space robotics for decades, most notably for building the robotic arms use on NASA’s Space Shuttles and the ISS, and has developed partnerships with many international entities.
    - In March 2019, the Canada Space Agency (CSA) released its national Space Strategy (CSA 2019a). Priorities include joining the Lunar Gateway, inspiring young Canadians, solving everyday problems, growing the space economy, and leadership in space-based data.
    - The strategy claims Canada’s space sector contributes $2.3 billion to Canada’s GDP and discusses other socioeconomic benefits of space such as Earth imagery for agriculture.
    - The 2019–2020 Department Plan outlines five priorities: The Lunar Gateway, launching RADARSAT, an ISS mission with a Canadian astronaut, participation in ESA’s 2019 Ministerial Council meeting, and collaborating on international space science missions (CSA 2019b).
    - CSA’s budget is trending downward, from $388 million in 2016–2017 down to $285 million in 2021–2022.
- OSAM Landscape
    - Current and Planned Activities

- Canadarm (Retroactively named Canadarm 1)
    - Canada was invited to participate in the Space Shuttle Program in 1969 and brought robotic technology from their nuclear power sector.
    - The first Shuttle Remote Manipulator System (formal title) was delivered in 1981. Five total Canadarms were built for the Space Shuttles.
    - Paired with the Orbit Boom Sensor System after the *Columbia* accident to inspect Space Shuttle thermal protection tiles.
- Mobile Servicing System on ISS – consists of the following subsystems:
    - Canadarm 2
        - Launched in 2001, seven motorized joints
        - Assisted with the docking of the space shuttle, can capture robotic vehicles like the Dragon and Cygnus capsules.
        - Latching end effectors
        - Enhanced Boom System
            - 50-foot arm extension, installed May 2011
            - Includes cameras for remote inspection of the station, based on boom used for Shuttle tile inspection.
    - Dextre
        - Launched in 2008, smaller, two-armed robot with power tools.
        - Capable of handling delicate assembly operations, such as changing the Orbital Replacement Units, currently performed by astronauts.
        - Testing tools for satellite servicing capabilities with NASA.
    - Mobile Remote Servicer Base System
        - Base platform for robotic arms, added in 2002.
        - Moves along the station’s 108-meter main truss.
        - Robotic arms can move to different base places in system.
- Advanced Space Vision System
    - Computer vision system designed to assemble the ISS
    - Based on elements to study car crashes in the 1970s.
- Canadarm 3 – in development for Lunar Gateway
    - Will have seven degrees of freedom, but other specific capabilities are still being discusses with international partners.

        - ISRU
            - Technology gap assessments and technology development, but no specific projects or programs.
            - Some studies with universities to do analog testing in Utah and Devon Island.
    - Key Institutions
        - Canadian Space Agency
            - Facilities in Longueuil, QB, Ottawa, ON, and Saskatoon, SK; a rocket range in Manitoba; and others.
        - MDA (HQ in Vancouver, BC)
            - MDA is owned by Maxar Technologies Inc. (headquartered in Westminster, CO), which formed in 2017 with the merger of the United States' DigitalGlobe and Canada's MDA Holdings Company.
            - MDA acquired SSL (headquartered in Palo Alto, CA) in 2012.
            - MDA's Robotics and Automation (a subsidiary of MDA headquartered in Brampton, ON) built Canadarm, the Mobile Servicing System on ISS (including Canadarm 2 and Dextre), and the Phoenix Mars Lander's meteorological station (and then acquired the company, Alliance Spacesystems LLC, that built the robotic arm).
    - Fit with Overall Goals
        - Canada's work in technologies relevant to OSAM builds on their long history of space robotics leadership.
        - Spin-offs to OSAM applications can help grow the space economy, one of the five priorities in their National Space Strategy.
        - Investments in base technologies can lead to diverse partnerships, with or without OSAM-specific applications that are likely to provide returns on investment.
- Investment and Funding
    - Government
        - Canada plans to spend $797M on lunar activities between now and 2024 (Canadian House of Commons 2019).
        - Targets $250M for Business Expenditures in Research and Development by March 31, 2020.
        - In February 2019, announced that $2.05B would be spent over 24 years to ensure Canada continues to be a leader in space robotics.
            - This includes $14M over 5 years to CSA to identify opportunities where space, health, and Indigenous partners could work collaboratively to address common problems.

            - $150M over 5 years for Lunar Exploration Accelerator Program to help small- and medium-sized entities develop new technologies.
    - Private
- Partnerships
    - Partners and Goals
        - NASA
        - ESA
            - Canada and Europe have been collaborating on space projects since before CSA and ESA were formed.
            - Canadian-European Space Agency Agreement (CSA 2019c):
                - Fosters Canadian space industry exports and facilitates access to European markets.
                - Canada renewed its treaty-level agreement with ESA until 2030.
                - Canada plans to spend $32M in new programs in FY 2020.
        - ISRO – partnerships on astronomy missions (CSA 2019d), but nothing in OSAM.
        - JAXA – CSA Signed MOU in 2012, renewed in 2018, for mutual cooperation in using satellites for environmental, ocean monitoring, and disaster management (Messier 2012).
        - Australian Space Agency – Signed MOU in 2018, no details other than to deeper collaborative ties (ASA 2018).
        - Moon Express – Signed MOU in 2018 for payloads to lunar surface (Moon Express 2018).
    - Gaps Addressed
        - Canada's partnerships seem to be aimed at filling niche roles in larger programs or technology and capability sharing in smaller programs.
- Drivers
    - Canada and CSA have technology transfer programs that are similar to the United States and NASA's for transferring government-developed technologies to the private sector.
- Barriers
    - There are no civil missions planned to use the technologies developed for the Canadarm program for any applications other than human spaceflight.
    - While space robotics are a national priority, commercial applications of OSAM do not appear be, though advances could be spun off more quickly compared to other countries because of their technological readiness.
    - Canada has fewer big companies compared to the U.S. that can drive demand for commercial OSAM activities and development.

Australia

- Context: Overall Space Landscape
    - Australia is building up its nascent space program with targeted investments, heavily leveraging their academic and industrial mining communities.
    - The civil Australian Space Agency was formed in July 2018 with an initial budget of $41.2 million over 4 years (Wicht 2018), with an additional injection of $19.5 million in 2019 through the Space Infrastructure Fund over 3 years (ASA 2019b).
    - The Australian Civil Space Strategy outlines Australia's 10-year vision for how to grow their space capabilities (ASA 2019a). SSA and debris monitoring are a part of this strategy, but not debris removal explicitly. Robotics and automation in space is another focus area.
    - Other investments in space activities dwarf these budgets, including $225 million for improved PNT, $36.9 million to improve Digital Earth Australia (Wicht 2018), and $150 million over 5 years to join the United States on missions to the Moon and Mars (NASA 2019b, Moon 2019).
- OSAM Landscape
    - Current and Planned Activities
        - Australia is active in both remote survey (R1) and ISRU (M). Currently, HEO Robotics is conducting remote survey of debris, and many universities and mining companies are doing research in robotics and automation but not necessarily for OSAM specifically at this point.
    - Key Institutions
        - Government – The Australian Space Agency formed in July 2018. The Agency has a budget of $15 million for 2019.
        - Private
            - HEO Robotics – A startup that conducting remote survey missions by renting spacecraft. HEO uploads software to a cooperative host satellite ("client") and uses their cameras to take images when they fly past the satellite of interest ("customer"). This method is very cheap, because they do not need their own hardware, but illegal in the United States, where they would need a remote sensing license in order to do this. Currently only working with Australian clients and customers. HEO is working with the Australian military and other customers to provide data, mostly on debris objects. Because of the low costs, their customers have paid in advance, unlike most other contract work where prices are too high and results too uncertain. This model undercuts most American business models and could possibly open up vulnerabilities to cyber threats.

      - Several new startups to conduct lunar ISRU, most of which are nascent and started within the past year from university research programs (Spero Space and Spaceflight Industries are examples). Other companies have extensive experience in remote mining operations that could be transferred to lunar ISRU activities and technology development.
    - Academic
      - University of New South Wales supports HEO Robotics and the Off-Earth Mining Working Group. Other institutes doing robotics for remote mining that could move to space include Curtin University School of Mines.
      - The Australian Remote Operations for Space and Earth (AROSE) consortium aims to partner with NASA to build a station in lunar orbit. The government of Western Australia hopes that the consortium will inject $200 million into the local economy and create 1500 jobs over the next 5 years (Tangermann 2020).
  - Fit with Overall Goals
    - Australia is building a wide range of capabilities but has a limited budget compared to the United States. It wants to grow its SSA capabilities and is prioritizing “Leapfrog R&D” in its civil space strategy.
- Investment and Funding
  - Government: It is unclear how much the Australian Space Agency will spend on OSAM activities specifically, though its budget is limited to ~$15 million per year and spread over seven strategic areas rather than any specific major projects.
  - Private: Little has been raised through venture capital for OSAM in Australia. HEO Robotics’ funding comes from advance purchases, the amounts of which were not disclosed. Other companies are spared some expenses by working with universities and graduate students.
- Partnerships
  - Partners and Goals
    - Partnerships with Australian universities help spread the true cost of developing a capable workforce by masking the source of funding in Australia’s education system while building a technical base that can be shifted to challenges in other fields as necessary.
  - Gaps Addressed
    - HEO Robotics is helping Australia’s strong SSA capabilities by complementing them with better imagery of space debris.
- Drivers

    - Partnerships with the United States, especially for lunar surface activities, could drive much of the ISRU robotics that is mostly nascent in Australia at a faster pace.
    - Space traffic management regulations could accelerate Australia's SSA capabilities and encourage more development of remote inspection systems.
- Barriers
    - New regulations in in Australia's remote sensing policy could disrupt HEO Robotics' activities by restricting them to activities with their own spacecraft. Relaxed regulations in other countries would create competition that could undercut their services.

New Zealand

- Context: Overall Space Landscape
    - The New Zealand Space Agency does not have a specific interest in OSAM, but as a nascent launching state, they want to stay abreast with regulatory implications for their launches and create a friendly regulatory environment for their customers.
    - New Zealand has manufacturing companies and research dedicated to robotics and off-Earth materials, but no concrete plans to pursue these activities in space yet.
    - New Zealand has no government satellites and no need for on-orbit servicing. The NZSA is focused on Earth and Earth science and how their space activities can benefit the NZ economy.
- OSAM Landscape
    - Current and Planned Activities
        - Policy development is the primary activity for the agency.
    - Key Institutions
        - New Zealand Space Agency
            - As of 10/17/19, New Zealand has approved of 34 payloads for launch (MBIE 2019a).
            - At least one payload launched from New Zealand is providing calibration points for ground-based radar to assist with orbital debris tracking (MBIE 2019b).
        - Private
            - New Zealand has 20–30 additive manufacturing companies that are working on parts for use in space. None of these companies has publicly released anything specific about doing additive manufacturing in space, but according to interviews, many are interested.
        - Academic
    - Fit with Overall Goals

        - New Zealand sees space as an extension of its economy and wants to create a friendly regulatory environment to attract launch customers and other businesses.
- Investment and Funding
    - Government
        - The agency's total budget is NZ$14 million over 4 years.
        - The agency has allocated NZ$3 million dollars for early stage R&D to fund ~6 projects, which have not been announced yet (and may not be related to OSAM).
    - Private
- Partnerships
    - Partners and Goals
        - NZSA is partnering with the United States and ESA to work on some policy towards debris mitigation.
        - NZSA has a partnership with DLR where on-orbit servicing was one of the mentioned topics, but it may not be a main focus in the future.
        - New Zealand has expressed an interest in wanting to ensure a good STM system goes into place.
    - Gaps Addressed
- Drivers
    - Regulatory environment: New Zealand has a very fast pipeline for its licensing, unlike in the United States, that could attract business and technologies.
- Barriers
    - Standards: International standards need to be developed with buy-in from many, not few, so that there are not competing standards.

Other Countries

STPI pursued leads for OSAM activities in other countries, including Brazil, the United Arab Emirates, South Africa, Mexico, Nigeria, Turkey, South Korea, Indonesia, and Israel, but found no significant activity. South Korea has some university involvement with ISRU initiatives, but STPI was unable to find any high-level involvement with any other OSAM activity. Algeria is involved through investments but not technology transfer or operations. Israel is involved as a partner for integration with a private company but not operations. Countries with nascent space programs like the UAE have stated interest in ISRU but no significant developments in it or any other reported stake in other OSAM activities. Many countries are building their additive manufacturing capabilities for space products to be built on the ground, but not for manufacturing in space.

Appendix D. OSAM Policy Trends Chart

Country	Current Status of Policy Regulation or OSAM Framework—Background Research	Observations regarding OSAM Policy from Interviewees[98]
United States (U.S.)	• No Federal U.S. entity has defined a clear regulatory pathway for on-orbit servicing. Until recently, servicers did not have explicit permission to do servicing (ex: Space Logistics). • Although the U.S. does not have concrete OSAM regulations in place, CONFERS has brought together public and private stakeholders "to research, develop, and publish non-binding, consensus-derived technical and operations standards for on-orbit servicing and RPO" (CONFERS 2020) • Space Policy Directive-3 (SPD-3) emphasizes importance of developing "debris mitigation guidelines, standards, and policies" that should be reviewed periodically, enforced domestically, and adopted internationally" (The White House 2018). While SPD-3 does not have the force of law, it is a reflection of the intent of the executive branch.	**U.S.** • One interviewee believed that any progress the U.S. makes on OSAM regulation could help the U.S. become a role model for international regulatory regimes. • One interviewee stated that existing policy statements are not sufficient for OSAM. Although Congress may want to give the Department of Commerce the authority to develop a "one-stop-shop" for licensing commercial space, that would require Congress to authorize changes in budgeting and authorities. **U.S.-UK comparison** • One interviewee believed the UKSA may be ahead of the U.S. since there is less bureaucratic overhead involved in licensing in the UK than in the U.S. The interviewee sensed that the UKSA already has the authority necessary to license and "it's only a matter of deciding which checkboxes are going to be on their licenses." Meanwhile in the U.S. the rift between the Administration and Congress prohibits progress developing an oversight regime. • When comparing where entities would prefer to locate

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[98] All information in the column "Observations regarding OSAM policy from interviewees" is based on information stated by interviewees.

Country	Current Status of Policy Regulation or OSAM Framework—Background Research	Observations regarding OSAM Policy from Interviewees[98]
		headquarters based on policy, the UK appears to be a more attractive option considering they have fewer bureaucratic hurdles. But when considering access to a large customer base, venture capital firms, and talent, the U.S. would be considered the better option.
United Kingdom (UK)	• The UK Space Agency (UKSA) is responsible for the government's civil space programs, which includes policy, regulation, and coordination with government departments (UK Space Agency 2015). • The National Space Security Policy document, a guiding policy document published in 2014, highlights the UK's "important objective" to help develop and clarify international regulatory regimes that deal with issues of "ownership, control, responsibility, authority, and liability," issues inherent to OSAM (UK Space Agency 2014). • The 2015 National Space Policy underlines the UK's commitment to safe operating environments that are free of interference and emphasize the country's commitment to remaining a strong advocate for the adoption of best practices by all state actors (UK Space Agency 2015).	**UK** • One interviewee said that the UKSA recognizes the need to develop regulations and policy around OSAM for UK companies. • One interviewee explained that the UK's space objectives are driven by a perception that the space sector will create high-paying jobs and wealth for the country. There is also a sense that the UK needs to be more self-sufficient and has a desire to have an independent GNSS, launch capabilities, etc. The interviewee provided the caveat that the desire to become more independent is likely to be affected by the UK space industry receiving more funding as of late despite space exploration and space science not being defined as goals of the UK space program. • One interviewee stated that the UK has been working on developing a regulatory pathway for on-orbit servicing for a while; they have a "stoplight chart" with different categories of missions they intend to service, but have not yet developed a pathway for servicing missions. • One interviewee clarified that OSAM entities in the UK have to go through the UK Space

Country	Current Status of Policy Regulation or OSAM Framework—Background Research	Observations regarding OSAM Policy from Interviewees[98]
		Agency (UKSA) and OfComm, the UK's communications regulator, for licensing.
Europe/ESA	• The European Union, European Commission, and European Space Agency collaborate in the development of policy (European Commission 2016). The European Space Agency's (ESA) role is to promote cooperation between European states, coordinate long-term European space policy with the activities of national programs, and recommend space objectives to Member States (European Space Agency 2020). • In May 2007, the European Commission and ESA Director jointly developed the Resolution on the European Space Policy that set out the vision and strategy for the space sector, including goals for satellite navigation, Earth observation, satellite communications, and the need to develop standards. It was the first time a common political framework for European space activities was developed (ESA Communications 2007; European Space Agency 2007). • In 2015, ESA published a Handbook to ensure ESA projects maintain compliance with the ESA's Space Debris Migration policy (ESA Space Debris Mitigation WG 2015). • In addition to delivering a roadmap to help coordinate the development of key enabling technologies needed for on-orbit servicing and planetary exploration, PERASPERA is tasked with recommending guidelines and standards for Europe's space sector, including recommendations	• One interviewee said that ESA leadership believes they have a responsibility to establish policy and assist companies working on OSAM. • One interviewee stated that PERASPERA is similar to CONFERS given its aim to consolidate the European perspective on OSAM standards.

Country	Current Status of Policy Regulation or OSAM Framework—Background Research	Observations regarding OSAM Policy from Interviewees[98]
	related to “regulation, licensing and standardization authorities for future on-orbit operations” under the European Operation Framework (EOF) (Horizon 2020 2020a; Horizon 2020 2020b). The EOF will bring together European stakeholders to generate guidelines, achieve a consolidated European position, and cooperate with related initiatives around the world.	
France	• The Centre National d’Etudes Spatiales (CNES) is the government agency responsible for regulating France’s space activities. Though it is unclear to what extent France is working on OSAM regulation, the French Space Operations Act (FSOA) of 2008 remains a key legislative framework for French space operators, French operators operating in foreign territory, and operations conducted on French territory (Lazare 2013). The Act aims to ensure operators are compliant with technical regulations set to protect persons, property, public health and the environment (Translated excerpt of the French Space Operation Act 2008). • CNES processes and manages changes to technical regulations; the Minister of Space makes a decision on recommendations offered by CNES to finalize the Technical Regulations (Mariez 2010; Lazare 2013) • The Act “creates a mandatory authorization scheme for space operators who [in turn] benefit from a government guarantee in the event of damage.” The authorization scheme mentions launch, operations, and the transfer of control of satellites,	• One interviewee did not believe that France has a specific licensing pathway in place but would not rule out the possibility of France working on a regulatory regime.

Country	Current Status of Policy Regulation or OSAM Framework—Background Research	Observations regarding OSAM Policy from Interviewees[98]
	all activities relevant to OSAM (Translated excerpt of the French Space Operations Act).	
Germany	• The Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR) is the government agency responsible for space affairs and regulating Germany's space activities. • The Federal Foreign Office works in "close partnership and coordination" with DLR to work on German space interests. Germany is working on a national outer space law that will specify the internal criteria for monitoring and liability (German Federal Foreign Office 2018).	• One interviewee acknowledged that leaders of the German space agency are thinking about the licensing process and DLR is in the midst of creating a specific remote sensing license. • One interviewee stated that Germany is working on a space law regarding liability of those who launch objects and end-of-life servicing. This could act as an incentive for German companies to consider sustainable approaches to building satellites (i.e. iBoss' iBLOCKs). Until now, progress on the space law has not been a political priority. One interviewee explained that Germany's approach to space and OSAM centers on competitiveness, growing German companies, and fostering commercialization in space.
Italy	• The Agenzia Spaziale Italiana (ASI) is the government agency responsible for Italy's space affairs, which includes the development and dissemination of research relevant to the space sector and coordination with ESA and the EU (Italian Space Agency n.d.) • In 2005, ASI signed onto the European Code of Conduct for Space Debris Mitigation whose goal was to "encourage the adoption of operational techniques that would limit the production of space debris." The United Kingdom, France, Germany, and ESA also signed onto the Code of Conduct	• One interviewee stated that the Italian government's guidelines on space and aerospace/space governance were modified in January 2018; they stated the direction of policy aligns more closely to the direction of the National Space Council.

Country	Current Status of Policy Regulation or OSAM Framework—Background Research	Observations regarding OSAM Policy from Interviewees[98]
	(United Nations Office for Outer Space Affairs 2019; United Nations Office for Outer Space Affairs 2004).	
Luxembourg	• The Luxembourg Space Agency (LSA) is the government agency responsible for Luxembourg's space affairs, including the management of R&D and implementing their space economic development strategy and policy (Luxembourg Space Agency 2020a). • In January 2020, the Luxembourg government announced a 5-year national action plan for space science and technology in the country that emphasizes an interest in telecommunications, space resources, and the development of the cubesat Juventas that will fly with ESA's Hera mission (Foust 2020). • In the national action plan, the third cornerstone of the proposed Space Security Program emphasizes the importance of maintaining and actively removing space debris; the program intends to plan a debris removal mission and support the emerging maintenance market (Luxembourg Space Agency 2020b).	• One interviewee explained that Luxembourg operates through a "bottom-up" approach; they assist entrepreneurs in developing their activities, but allow entrepreneurs' activities to guide policy rather than the converse.
Japan	• The Japan Aerospace Exploration Agency (JAXA) is the core agency that supports the Japanese government's aerospace development, R&D, and utilization, including its OSAM activities (Japanese Aerospace Exploration Agency n.d.). • For debris removal, there currently is no regulation forcing companies to remove debris (Blackerby and Okada n.d.). However, in 2011 JAXA	• One interviewee stated that they believed Japan has given regulation "quite a lot" of thought, but was unsure whether JAXA would be the regulatory body for OSAM. • One interviewee stated that the regulatory body for OSAM would be the National Space Policy Secretariat of the Cabinet Office of Japan. • One interviewee stated that the Space Activity Law regulates the overall types of

Country	Current Status of Policy Regulation or OSAM Framework—Background Research	Observations regarding OSAM Policy from Interviewees[98]
	updated its Space Debris Mitigation Standard (JMR-003B), an internal JAXA document that requires projects to have debris mitigation plans in place. Japanese government administrations follow this guideline when procuring spacecraft. • In November 2016, Japan enacted the Act on Launching Artificial Satellites and Managing Satellites and the Act on Securing Proper Handling of Satellite Remote Sensing Records, which were designed to promote commercial space activities and establish licensing procedures (Wakimoto 2019).	control of satellites and that OSAM is covered under that law. Review of technical standards may be considered depending on future OSAM trends.
Australia	• The newly established (2018) Australian Space Agency is the government agency responsible for providing national policy and strategic advice to the government on the civil space sector, facilitating coordination, and administering space activities legislation (Australian Space Agency 2020). • The Space Activities Act of 1998, which preceded the establishment of the Australian Space Agency, is the existing legal framework in which Australian space activities operate. It includes guidelines on launch, licensing, and liability (Federal Register of Legislation 2016). The Australian Space Agency's Civil Space Strategy for 2018-2028 released in April 2019 mentions that the agency is responsible for amending the 1998 Act during Phase 1 of its strategy, designated to be completed between 2018-2019 (Australian Space Agency 2019). • The Strategy highlights SSA and debris monitoring as priority areas, and in phases 2 and 3 of	• One interviewee said that the establishment of a restrictive remote sensing policy could be disruptive to some Australian companies. Relaxed OSAM regulations in other countries would also create competition that could undercut some Australian companies' services.

Country	Current Status of Policy Regulation or OSAM Framework—Background Research	Observations regarding OSAM Policy from Interviewees[98]
	their strategy (intended to be carried out between 2019-2021 and 2021-2028 respectively) they intend to establish a regulatory framework that meets their international obligations and ensures "effective, efficient, and safe space activities" (Australian Space Agency 2019). It is currently unclear to what extent this regulatory framework will oversee OSAM activities.	
New Zealand	• The New Zealand Space Agency is the government agency responsible for space policy, regulation, and business development (Ministry of Business, Innovation & Employment n.d.) • The Outer Space and High-Altitude Activities Act 2017 (OSHAA) establishes a licensing regime that covers space launches, launch facilities, payloads, and a legal framework to regulate high-altitude activities originating from New Zealand (New Zealand Parliament n.d.). This regime was established to comply with New Zealand's international obligations, manage risk, enable different launch providers to operate out of New Zealand, and support New Zealand's intention to design, manufacture, and launch its own satellites (Hutchinson et al. 2017).	• One interviewee said that given competing priorities (e.g., a launch infrastructure, Earth remote sensing and communication), New Zealand doesn't have a need to engage in OSAM activities.
Singapore	• Singapore does not have a national space agency or a national space law in place. It has telecommunications regulations in place, but does not have regulations regarding OSAM.	• One interviewee stated that because they are interested in activities related to active debris removal, a framework requiring the removal of satellites would help the market. • One interviewee stated that they did not believe Singapore would neglect

Country	Current Status of Policy Regulation or OSAM Framework—Background Research	Observations regarding OSAM Policy from Interviewees[98]
		OSAM but does not see the market as big enough yet.
Canada	• The Canadian Space Agency (CSA) is the national space agency responsible for assisting the Minister to "coordinate the space policies and programs" of the Canadian government (Canadian Space Agency 1990). • In 2005, Canada established remote sensing space systems regulations that detailed requirements for licensing. One requirement includes a remote sensing satellite disposal plan for entities interested in a license; it also outlines that an entity cannot directly or indirectly operate without a license. The Act was subsequently updated in 2007 (Canadian Space Agency 2007). • In March 2019, the CSA released its Space Strategy, which states that Canada will invest in regulatory reform. The government "will review Canada's regulatory framework for space-related activities," and will, "examine whether the regulatory system is keeping pace with emerging technologies and new business models in the space sector (Canadian Space Agency 2019).	• One interviewee stated that although satellite servicing, assembly, solar power beaming, deorbiting, ADR, assembly, and servicing have been considered and are within the realm of possibility, concrete plans have not been defined thus far.
Russia	• The Roscosmos State Corporation for Space Activities (Roscosmos) is considered "the [principal] coordinating hub for space activities in Russia" (Howell 2018). In 2016, Russia made Roscosmos a state corporation with "all space industry united in one framework…making the policy and procurement decisions (McClintock 2017).	• No interviews conducted with Russian entities

Country	Current Status of Policy Regulation or OSAM Framework—Background Research	Observations regarding OSAM Policy from Interviewees[98]
	• In 2016, Russia approved its first space strategy, FKP-2025, projecting its goals for the next 10 years (Zak 2016). Goals outlined include ensuring state policy supports space activities, modernizing technological capabilities of satellites and satellite constellations, improving communications systems, and furthering R&D for critical technologies (Roscosmos 2016). The document highlights communications and broadcasting satellites as its first priority and has divided its goals into two stages (2016–2020 and 2020–2025), though it is unclear to what extent OSAM activities are included in this strategy or how they will be managed. • Beginning in 2019, Russia established technical guidelines to mitigate near-earth space debris. • Since to the best of our knowledge there are no private actors in the OSAM domain, regulations specifically relating to OSAM are lacking.	
China	• China's policy and regulation operates in a top-down process. The Ministry of Science and Technology carries out policy decisions made by the Communist Part of China (CPC), which is not limited organizing the development of plans, policies, and measures needed for S&T as well as working with relevant departments (Ministry of Science and Technology of the People's Republic of China 2018). • In 2016, China's State Council published its thirteenth 5-year plan for Science, Technology and Innovation. Of the 16	• No interviews conducted with Chinese entities.

Country	Current Status of Policy Regulation or OSAM Framework—Background Research	Observations regarding OSAM Policy from Interviewees[98]
	Megaprojects to be launched by 2020, one focuses on on-orbit servicing and maintenance systems of spacecraft (China Innovation Funding n.d.). • STPI's research found no private actors in the OSAM domain, so explicit regulations specifically relating to OSAM are lacking.	
India	• India is interested in allowing more private entities to support their space sector and space activities. There have been calls for the development of space policy that would help "expand the industry" given the lack of "a comprehensive space policy" (Anilkumar and Singai 2010). • The development of a national space policy, the 2017 Space Activities Bill, is now under consideration by its parliament to encourage the participation of Indian industry and startups. The policy would also establish a licensing regime that would oversee the performance and activities of private companies (Prasad 2019).	• No interviews conducted with Indian entities

Appendix E. Identifying Drivers

Each driver may have an influence on one or more OSAM elements, but each driver can also influence other drivers, creating competing forces that make it difficult to predict the directions in which the sum of all drivers will influence OSAM development.

To better characterize these potentially competing relationships, STPI created a design structure matrix (DSM) to qualitatively characterize how each driver influences OSAM development as well as each other driver. In STPI's matrix, each cell is filled in with one of the following values:

- 0 indicates no relationship between the row driver and the column
- 1 indicates a weak relationship
- 3 indicates a substantial relationship
- 9 indicates a strong relationship

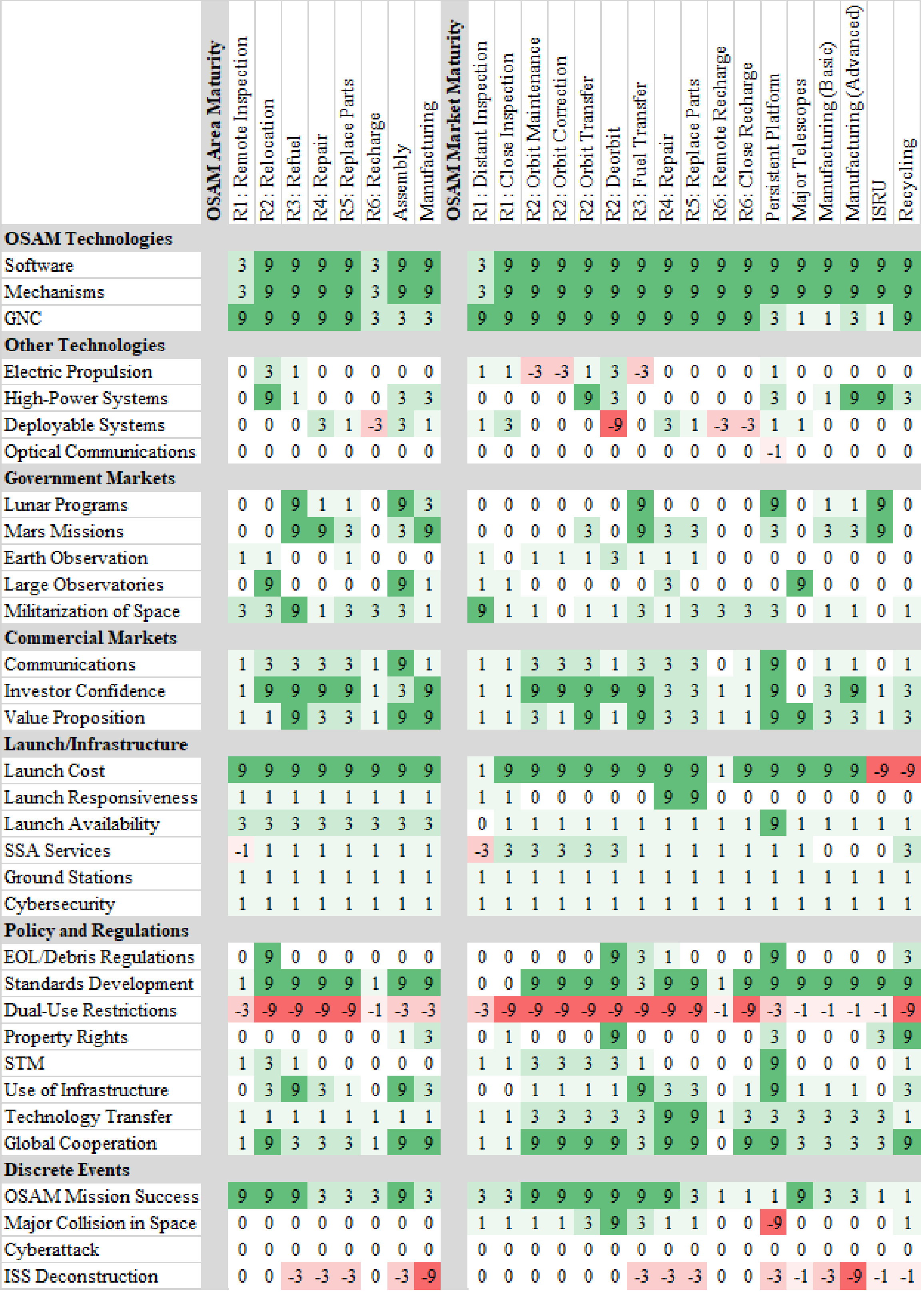
A negative number indicates that the growth of the row driver has the opposite effect on the column driver. A nonlinear scale was chosen to be consistent with other engineering design methods like the House of Quality (Hauser and Clausing 1988).

Because not all driver relationships are one-to-one, the matrix is not transposable (i.e., it is not mirrored across the diagonal line from top-left to bottom-right). For example, falling launch costs will greatly affect technology development, but technology development will likely not affect launch costs (unequal relationship); the risk from space debris will increase the market for deorbit services, but deorbit services will decrease the risk from space debris (opposite relationship).

The full DSM is available as a separate file because it is too large to fit here. Table F-1 shows a section of the full DSM describing the relationship each driver has on OSAM technologies and markets. From this table, the drivers that are most directly influential to OSAM can be seen by virtue of how strong the relationships are across the board. Additionally, this section shows drivers that one would expect to hinder most OSAM activity having positive influences on certain OSAM markets and technologies.

The full DSM can be used as a tool to study how different developments could affect future OSAM activities. Given the breadth of global activities in OSAM and the complexity of events that affect such a nascent field, STPI cannot describe every plausible future scenario. However, the DSM can be partitioned to identify the strongest drivers and feedback loops between drivers that can create counterintuitive effects. Some of those likely scenarios and feedback are shown below.

Table E-1. Section of DSM for Driver Influence on OSAM



	OSAM Area Maturity	R1: Remote Inspection	R2: Relocation	R3: Refuel	R4: Repair	R5: Replace Parts	R6: Recharge	Assembly	Manufacturing	**OSAM Market Maturity**	R1: Distant Inspection	R1: Close Inspection	R2: Orbit Maintenance	R2: Orbit Correction	R2: Orbit Transfer	R2: Deorbit	R3: Fuel Transfer	R4: Repair	R5: Replace Parts	R6: Remote Recharge	R6: Close Recharge	Persistent Platform	Major Telescopes	Manufacturing (Basic)	Manufacturing (Advanced)	ISRU	Recycling
OSAM Technologies																											
Software		3	9	9	9	9	3	9	9		3	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9
Mechanisms		3	9	9	9	9	3	9	9		3	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9
GNC		9	9	9	9	9	3	3	3		9	9	9	9	9	9	9	9	9	9	9	3	1	1	3	1	9
Other Technologies																											
Electric Propulsion		0	3	1	0	0	0	0	0		1	1	-3	-3	1	3	-3	0	0	0	0	1	0	0	0	0	0
High-Power Systems		0	9	1	0	0	0	3	3		0	0	0	0	9	3	0	0	0	0	0	3	0	1	9	9	3
Deployable Systems		0	0	0	3	1	-3	3	1		1	3	0	0	0	-9	0	3	1	-3	-3	1	1	0	0	0	0
Optical Communications		0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0
Government Markets																											
Lunar Programs		0	0	9	1	1	0	9	3		0	0	0	0	0	0	9	0	0	0	0	9	0	1	1	9	0
Mars Missions		0	0	9	9	3	0	3	9		0	0	0	0	3	0	9	3	3	0	0	3	0	3	3	9	0
Earth Observation		1	1	0	0	1	0	0	0		1	0	1	1	1	3	1	1	1	0	0	0	0	0	0	0	0
Large Observatories		0	9	0	0	0	0	9	1		1	1	0	0	0	0	0	3	0	0	0	0	9	0	0	0	0
Militarization of Space		3	3	9	1	3	3	3	1		9	1	1	0	1	1	3	1	3	3	3	3	0	1	1	0	1
Commercial Markets																											
Communications		1	3	3	3	3	1	9	1		1	1	3	3	3	1	3	3	3	0	1	9	0	1	1	0	1
Investor Confidence		1	9	9	9	9	1	3	9		1	1	9	9	9	9	9	3	3	1	1	9	0	3	9	1	3
Value Proposition		1	1	9	3	3	1	9	9		1	1	3	1	9	1	9	3	3	1	1	9	9	3	3	1	3
Launch/Infrastructure																											
Launch Cost		9	9	9	9	9	9	9	9		1	9	9	9	9	9	9	9	9	1	9	9	9	9	9	-9	-9
Launch Responsiveness		1	1	1	1	1	1	1	1		1	1	0	0	0	0	0	9	9	0	0	0	0	0	0	0	0
Launch Availability		3	3	3	3	3	3	3	3		0	1	1	1	1	1	1	1	1	1	1	9	1	1	1	1	1
SSA Services		-1	1	1	1	1	1	1	1		-3	3	3	3	3	3	1	1	1	1	1	1	1	0	0	0	3
Ground Stations		1	1	1	1	1	1	1	1		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Cybersecurity		1	1	1	1	1	1	1	1		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Policy and Regulations																											
EOL/Debris Regulations		0	9	0	0	0	0	0	0		0	0	0	0	0	9	3	1	0	0	0	9	0	0	0	0	3
Standards Development		1	9	9	9	9	1	9	9		0	0	9	9	9	9	3	9	9	1	9	9	9	9	9	9	9
Dual-Use Restrictions		-3	-9	-9	-9	-9	-1	-3	-3		-3	-9	-9	-9	-9	-9	-9	-9	-9	-1	-9	-3	-1	-1	-1	-1	-9
Property Rights		0	0	0	0	0	0	1	3		0	1	0	0	0	9	0	0	0	0	0	3	0	0	0	3	9
STM		1	3	1	0	0	0	0	0		1	1	3	3	3	3	1	0	0	0	0	9	0	0	0	0	1
Use of Infrastructure		0	3	9	3	1	0	9	3		0	0	1	1	1	1	9	3	3	0	1	9	1	1	1	0	3
Technology Transfer		1	1	1	1	1	1	1	1		1	1	3	3	3	3	3	9	9	1	3	3	3	3	3	3	1
Global Cooperation		1	9	3	3	3	1	9	9		1	1	9	9	9	9	3	9	9	0	9	9	3	3	3	3	9
Discrete Events																											
OSAM Mission Success		9	9	9	3	3	3	9	3		3	3	9	9	9	9	9	9	3	1	1	1	9	3	3	1	1
Major Collision in Space		0	0	0	0	0	0	0	0		1	1	1	1	3	9	3	1	1	0	0	-9	0	0	0	0	1
Cyberattack		0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ISS Deconstruction		0	0	-3	-3	-3	0	-3	-9		0	0	0	0	0	0	-3	-3	-3	0	0	-3	-1	-3	-9	-1	-1

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Abbreviations

ADR	active debris removal
ADRIOS	Active Debris Removal/In-Orbit Servicing
AEHF	advanced extremely high frequency
AI	artificial intelligence
ASI	Italian Space Agency
CADET	CApture and Deorbiting Technologies
CAS	Chinese Academy of Sciences
CASC	China Aerospace Science and Technology Corporation
CASIC	The Chinese Aerospace Science and Industry Corporation
CDTI	Spain's space agency
CNES	National Centre for Space Studies
CONFERS	Consortium for Execution of Rendezvous and Servicing Operations
COPUOS	Committee on the Peaceful Uses of Outer Space
CSA	Canada Space Agency
DARPA	Defense Advanced Research Projects Agency
DART	Double Asteroid Redirection Test
DFKI	German Research Centre for Artificial Intelligence
DLR	German Aerospace Center
DSM	design structure matrix
EOF	European Operations Framework
EOL	end-of-life
ESA	European Space Agency
FAA	Federal Aviation Administration
Gbps	billions of bits per second
GEO	geosynchronous Earth orbit
GNC	guidance, navigation, and control
GSSAP	U.S. Geosynchronous Space Situational Awareness Program
iBLOCKs	iBOSS functional Building Blocks
iBOSS	Intelligent Building Blocks for On-Orbit Satellite Servicing and Assembly
IDA	Institute for Defense Analyses
iSAT	In-Space Astronomical Telescope
ISRO	Indian Space Research Organisation
ISRU	in-situ resource utilization
ISS	International Space Station
iSSI	intelligent Space System Interface
JAXA	The Japan Aerospace Exploration Agency

JWST	James Webb Space Telescope
KiSSD	Kinetic Solution for Space Debris
LEO	low Earth orbit
LSA	Luxembourg Space Agency
MEV	Mission Extension Vehicle
NASA	National Aeronautics and Space Administration
NRO	National Reconnaissance Office
OMAR	On-orbit Manufacturing Assembly and Recycling
OSAM	on-orbit servicing, assembly, and manufacturing
OSTP	Office of Science and Technology Policy
POLSA	Poland’s space agency
R&D	research and development
ROTEX	RObotic TEchnology Experiment
RPO	rendezvous and proximity operations
RSGS	Robotic Servicing of Geosynchronous Satellites
SIROM	Standard Interface for Robotic Manipulation of Payloads in Future Space Missions
SRC	strategic research cluster
SSA	space situational awareness
SSTL	Surrey Satellite Technology Ltd
STM	space traffic management
STPI	Science and Technology Policy Institute
TRL	technology readiness level
UKSA	UK Space Agency
UNOOSA	United Nations Office for Outer Space Affairs

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13. SUPPLEMENTARY NOTES

14. ABSTRACT

Given the perceived importance of on-orbit servicing, assembly, and manufacturing (OSAM) in the evolving space sector, the IDA Science and Technology Policy Institute (STPI) began an assessment of global trends in OSAM. The goals of the study were to examine the key players currently pursuing or interested in on-orbit activities, their countries of origin, the levels of their efforts (technical and financial), their motivations, nascent projects, and planned efforts. We also assessed the potential market and use cases for on-orbit activities, including potential consumer needs and applications, as well as demand from public and private entities. STPI conducted over 65 formal unclassified interviews with experts from government and industry, spoke with representatives at space conferences and workshops, and reviewed the available literature to understand current OSAM activities internationally and to determine trends in the sector. STPI aimed to identify and predict, to the extent feasible, global trends in technology, market, and policy relevant to on-orbit activities.

15. SUBJECT TERMS

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