United States Government Accountability Office

Report to Congressional Addressees

July 2025

TECHNOLOGY ASSESSMENT

In-Space Servicing, Assembly, and Manufacturing

Benefits, Challenges, and Policy Options

GAO-25-107555

The cover image displays a representation of robotic arms servicing a satellite servicing in space.

Cover source: Dimazel/Phonlamaiphoto/stock.adobe.com (images). | GAO-25-107555

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Highlights of GAO-25-107555, a report to congressional addressees

July 2025

Why GAO did this study

ISAM technology and capabilities could change the paradigm of how spacecraft are designed, built, operated, and discarded. Since the advent of artificial satellites, almost all have been “single use”: assembled on Earth, sustained in space with no outside intervention beyond communication, and discarded or abandoned when no longer functional. ISAM could reduce cost and risk, increase flexibility, and help to better address failures after launch.

NASA and others have used ISAM capabilities for over 40 years, but largely involving crewed missions rather than uncrewed robotic missions. For example, astronauts repaired or upgraded the Hubble Space Telescope five times between 1993 and 2009.

This report describes potential benefits and status of ISAM capabilities as well as challenges facing their development and use. It also identifies options policymakers could consider that might help realize benefits and address challenges.

To conduct this technology assessment, GAO searched the relevant literature; reviewed documents and reports; interviewed federal officials, industry representatives, and stakeholders in academia and at federally funded research and development centers; conducted site visits; attended conferences and workshops; and convened a 2-day meeting of 20 experts from government, industry, academia, and federally funded research and development centers. GAO excluded sensitive and classified information. GAO is identifying policy options in this report.

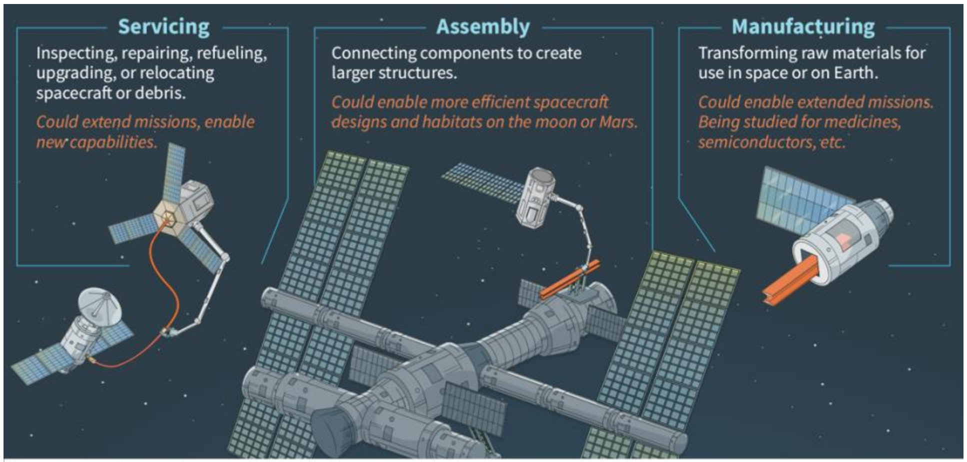
View GAO-25-107555. For more information, contact Karen L. Howard, PhD, at HowardK@gao.gov.

What GAO found

Space is increasingly important to the daily lives of Americans, to the economy, and to national defense. The number of active satellites in space providing critical services increased from 1,400 in 2015 to more than 11,000 in 2025. An additional 18,000 or more are projected to be launched by 2030, according to market analyses.

In-space servicing, assembly, and manufacturing (ISAM) technology has the potential to improve current satellite capabilities and to open new capabilities, such as orbital debris removal, space-based solar energy, larger space telescopes, and human deep-space exploration. In 2022, the Office of Science and Technology Policy published a national strategy and an implementation plan to guide federal ISAM activities. The plan named various agencies, including the Department of Defense (DOD) and the National Aeronautics and Space Administration (NASA), to lead these activities. DOD and NASA have spent more than $2 billion developing in-space servicing demonstration missions over the past decade, according to agency documentation and officials. Other countries are also developing and demonstrating ISAM technologies.

Definitions of in-space servicing, assembly and manufacturing



Source: GAO (analysis and illustration). | GAO-25-107555

While astronauts have repaired the Hubble Space Telescope and assembled and maintained the International Space Station, robotic ISAM functions are less mature. Robotic in-space servicing is not routinely used and has only been demonstrated on a handful of missions, but it is more mature than assembly and manufacturing.

Development of ISAM technology faces challenges largely related to what experts called a chicken-and-egg problem. Potential ISAM service providers are hesitant to develop the technology into servicing products (e.g., a satellite that can bring fuel to other satellites) until there is a user base (e.g., a refuelable satellite). Similarly, potential users are hesitant to design and deploy satellites that can be serviced until those products are available.

GAO identified four challenges contributing to this situation:

- Government agencies and industry have differing priorities for ISAM technology, and a single technology is unlikely to meet all priorities. This situation fragments demand for any given technology.
- Government and private satellite operators are generally not requiring that satellites be designed for future servicing, such as refueling or upgrading.
- Few in-space test opportunities are available for developers to test ISAM technology. As a result, ISAM providers have generally not demonstrated the capability to perform satellite servicing, which deters risk-averse satellite operators from committing to purchasing such servicing.
- Regulations and standards are unclear or emerging, both for space activities broadly and ISAM specifically.

GAO developed five policy options that could help address these challenges. These policy options are not recommendations. GAO presents them to help policymakers consider and choose options appropriate to the goals they hope to achieve. Policymakers may include legislative bodies, government agencies, standards-setting organizations, and industry.

Policy options to help address challenges with in-space servicing, assembly, and manufacturing (ISAM) technology development and use

Policy Option	Opportunities	Considerations
Maintain status quo efforts (report p. 24) For example, federal agencies, ISAM providers, and other policymakers could sustain current planned demonstration missions and ISAM community efforts.	• Current efforts may address some challenges without additional resources. • Resources that would have been allocated to further developing ISAM could be used for other opportunities.	• Current efforts are not likely to address all challenges, such as not being able to promptly respond to changing mission needs or satellite failures.
Evaluate, and potentially promote, serviceability (report p. 25) For example, federal agencies could study the economic benefits and costs of serviceability and then take actions, such as requiring that satellites be serviceable to enable repair, maintenance, or future technology upgrades.	• Evaluations of benefits could clarify whether and when serviceability can generate return on investment, which would help inform decisions about which other policy options to pursue. • Requirements could establish a user base and incentivize servicing providers. • Could be relatively inexpensive compared to the overall cost of a satellite.	• Historical data may not be sufficient to generate reliable evaluations. • Some benefits of satellite servicing may not be easily quantifiable.
Support technology development and testing (report p. 27) For example, the ISAM community could take steps to support testing opportunities on the ground and in space.	• More testing could enable smaller companies and academic research groups to participate in developing ISAM capabilities. • Could reduce technical risk, satisfy many potential users, and encourage adoption.	• Resources dedicated to test facilities and demonstrations would not be available for other agency or company priorities. • Demonstrations would not guarantee adoption by users.
Develop or clarify regulations and standards (report p. 28) For example, government agencies and standards organizations could clarify licensing or promulgate standards.	• Could lower barriers for ISAM providers.	• Government and industry may not be prepared to specify regulations or standards. • The ISAM industry is still developing, and regulations may inadvertently create unnecessary barriers to developing technology.
Designate a government champion (report p. 29) For example, Congress or the White House could designate a government champion to support ISAM development and coordinate with the Consortium for Space Mobility and ISAM Capabilities.	• The government champion could oversee and coordinate activities described in the ISAM National Strategy and the National ISAM Implementation Plan, and the policy options identified in this report.	• A government champion without sufficient authority, resources, and clear direction could be ineffective.

Source: GAO. | GAO-25-107555

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Abbreviations

COSMIC	Consortium for Space Mobility and ISAM Capabilities
DARPA	Defense Advanced Research Projects Agency
DOD	Department of Defense
FCC	Federal Communications Commission
GEO	geosynchronous orbit
ISAM	in-space servicing, assembly, and manufacturing
LEO	low Earth orbit
NASA	National Aeronautics and Space Administration
OSAM-1	On-Orbit Servicing, Assembly, and Manufacturing 1
OSTP	Office of Science and Technology Policy

U.S. GOVERNMENT ACCOUNTABILITY OFFICE

441 G St. N.W.
Washington, DC 20548

July 10, 2025

Congressional Addressees

Space is increasingly important to the daily lives of Americans, to the economy, and to national defense. The thousands of satellites currently in orbit provide critical services like communication, navigation, timing, and observations used for weather forecasting.[1] Future improvements in space technology could open new capabilities, such as the harvesting of space-based solar energy, manufacture of better medicines, and human deep-space exploration.

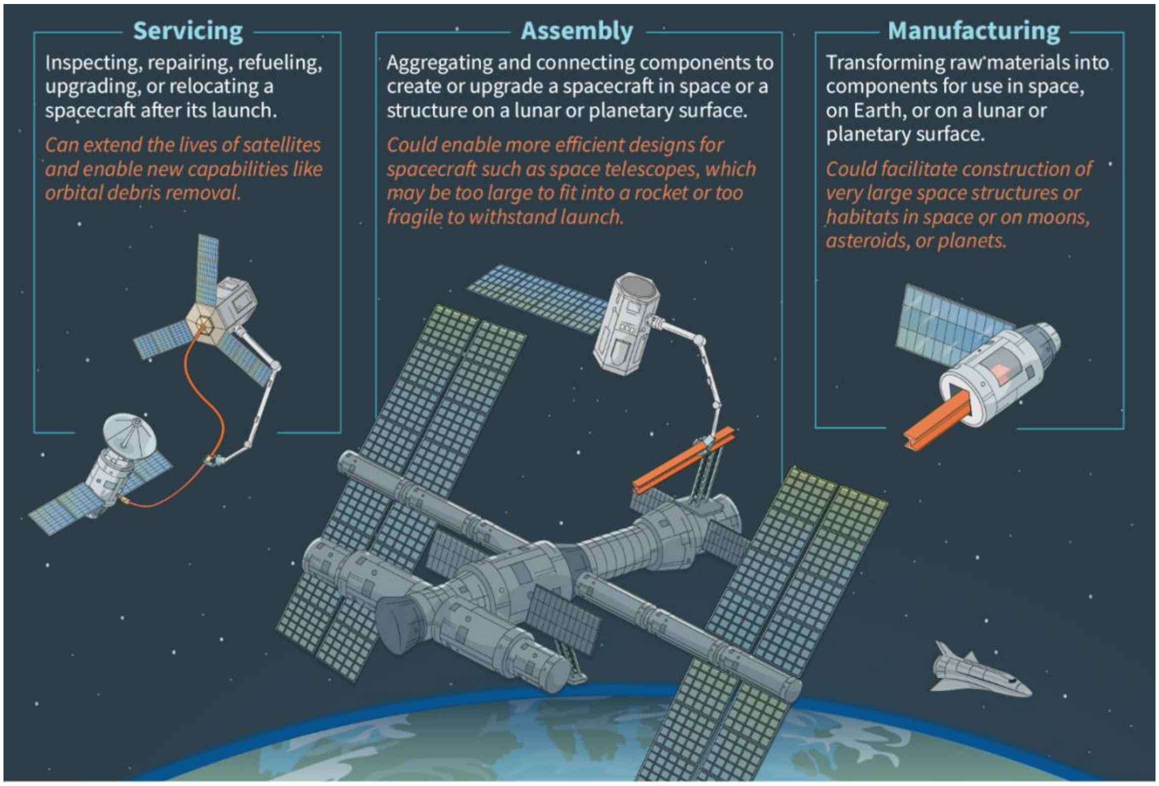
However, many such capabilities would require a shift away from the current paradigm of “single use”–launching complete satellites from Earth and never touching them again, other than via rare and expensive crewed missions. The new paradigm would include making satellites that can be serviced by other satellites, launching novel types of satellites in pieces for later robotic assembly, and the manufacture of materials and products in space. The technologies and capabilities required for this shift are collectively known as in-space servicing, assembly, and manufacturing (ISAM) (see fig. 1).[2] ISAM could extend the lives of satellites, improve cost effectiveness of space activities, enable greater mobility, facilitate removal of space debris, enable much larger space telescopes, and facilitate construction of other very large structures in space, on the moon, or on other planets. However, the development of ISAM faces various challenges, and its potential benefits have not been fully weighed against the costs.

We conducted an assessment of ISAM technologies at the initiative of the Comptroller General. This report describes potential benefits and status of ISAM capabilities as well as challenges facing their development and use. It also identifies options policymakers could consider that might help realize benefits and address challenges.

[1]The term “satellite” technically refers to all objects in orbit around a planet, including natural objects like the moon. “Spacecraft” is a term for artificial objects in space, including artificial satellites, space telescopes, space stations, and deep-space vehicles. In keeping with common usage, we use the term “satellite” as a synonym for “spacecraft” in orbit.

[2]ISAM is also referred to as on-orbit servicing, assembly, and manufacturing (OSAM). Space Access, Mobility, and Logistics (SAML) is the Department of Defense’s term for a mission area that heavily overlaps with ISAM.

Figure 1: Definitions of in-space servicing, assembly, and manufacturing



Source: GAO (analysis and illustration). | GAO-25-107555
Note: "Spacecraft" denotes an artificial satellite, space telescope, space station, or deep-space vehicle.

We primarily focused this technology assessment on technologies and capabilities for servicing, because they are more mature than those directly supporting assembly or manufacturing. We also focused on public U.S. ISAM activities rather than any classified activities. We conducted a background literature search; reviewed documents and reports; interviewed federal agency officials, industry representatives, stakeholders in academia, stakeholders at federally funded research and development centers, and a university affiliated research center; conducted site visits; attended conferences and workshops; and convened a 2-day meeting of 20 experts. See appendix I for a full discussion of the objectives, scope, and methodology. See appendix II for a list of experts who participated in our meeting and provided additional assistance.

We conducted this technology assessment from April 2024 to July 2025 in accordance with all sections of GAO's Quality Assurance Framework that are relevant to technology assessments. The framework requires that we plan and perform the engagement to obtain sufficient and appropriate evidence to meet our stated objectives and to discuss any limitations to our work. We believe that the information and data obtained, and the analysis conducted, provide a reasonable basis for any findings and conclusions in this product.

1 Background

1.1 Current state of space

Most people will never get the opportunity to go to space, yet their lives are increasingly connected to what happens there. Spacecraft in orbit (which are also commonly referred to as satellites) help people message their friends, watch TV, get driving directions, and decide whether they need an umbrella. Satellites also help with scientific research, crop predictions, wildfire detection, and military reconnaissance.

Over the last decade, the number of active satellites providing such services has grown rapidly—from around 1,400 in 2015 to more than 11,000 in March 2025.[3] The Hubble Space Telescope has been occasionally serviced, and the International Space Station is regularly repaired, refueled, and upgraded. However, most satellites are designed and manufactured for single use—discarded or abandoned after they can no longer perform their designated functions or have used all their fuel. ISAM could provide new capabilities to many of these satellites.

A majority of Earth's satellites are located in two common families of orbits: low Earth orbit (LEO) and geosynchronous orbit (GEO).[4] LEO is the most populated and extends from Earth's surface to 2,000 kilometers (1,240 miles) above the Earth's surface. GEO is the second most populated and is located around 36,000 kilometers (22,320 miles) above the surface. Satellites in LEO complete one orbit approximately every 90 to 120 minutes, whereas GEO satellites complete an orbit in approximately 24 hours, allowing them to stay above the same approximate place on Earth. The collective orbits of LEO satellites surround the Earth like a multilayered shell, while many GEO satellites orbit in a single ring above the Earth's equator (see fig. 2). As of March 2025, more than 10,000 active satellites orbited in LEO and more than 500 in GEO.[5] An additional 18,000 or more satellites are projected to be launched by 2030, likely primarily into LEO, according to market analyses.[6]

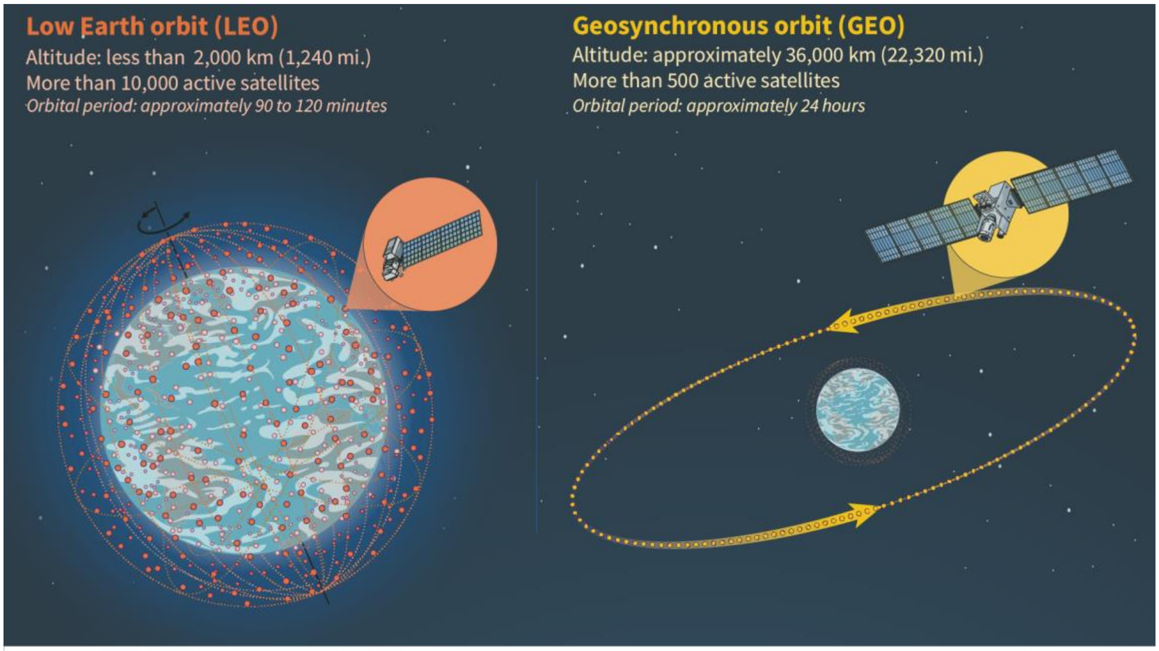
[3]Jonathan McDowell, *Active Sats versus Orbit Type*, General Catalog of Artificial Space Objects Release 1.7.0, accessed March 26, 2025. https://planet4589.org/space/stats/oactive.html.

[4]Another orbital type, medium Earth orbit, is located between LEO and GEO (i.e., from 2,000 to about 36,000 kilometers above the Earth's surface, or 1,240 to 22,320 miles). It contains satellites such as those that are part of GPS. The abbreviation "GEO" can refer to either geosynchronous orbits (any circular orbit at around 36,000 kilometers altitude) or geostationary orbits (the subset of geosynchronous orbits that are directly above the Earth's equator). We use "GEO" to refer to the broader category, geosynchronous orbits.

[5]There are additional satellites in other, less common orbits, for example, approximately 260 in medium Earth orbit.

[6]Goldman Sachs Research, "The global satellite market is forecast to become seven times bigger," (Mar. 5, 2025), https://www.goldmansachs.com/insights/articles/the-global-satellite-market-is-forecast-to-become-seven-times-bigger. Novaspace, "Novaspace forecasting a daily average of 7 tons of satellites will be launched," *satnews* (Sep. 17, 2024), https://news.satnews.com/2024/09/17/novaspace-forecasting-a-daily-average-of-7-tons-of-satellites-will-be-launched/. Chris Daehnick, John Gang, and Ilan Rozenkopf, "Space launch: Are we heading for oversupply or a shortfall?," McKinsey & Company Aerospace & Defense (Apr. 17, 2023), https://www.mckinsey.com/industries/aerospace-and-defense/our-insights/space-launch-are-we-heading-for-oversupply-or-a-shortfall. The exact number of active satellites in 2030 may differ from the proposed number of satellites.

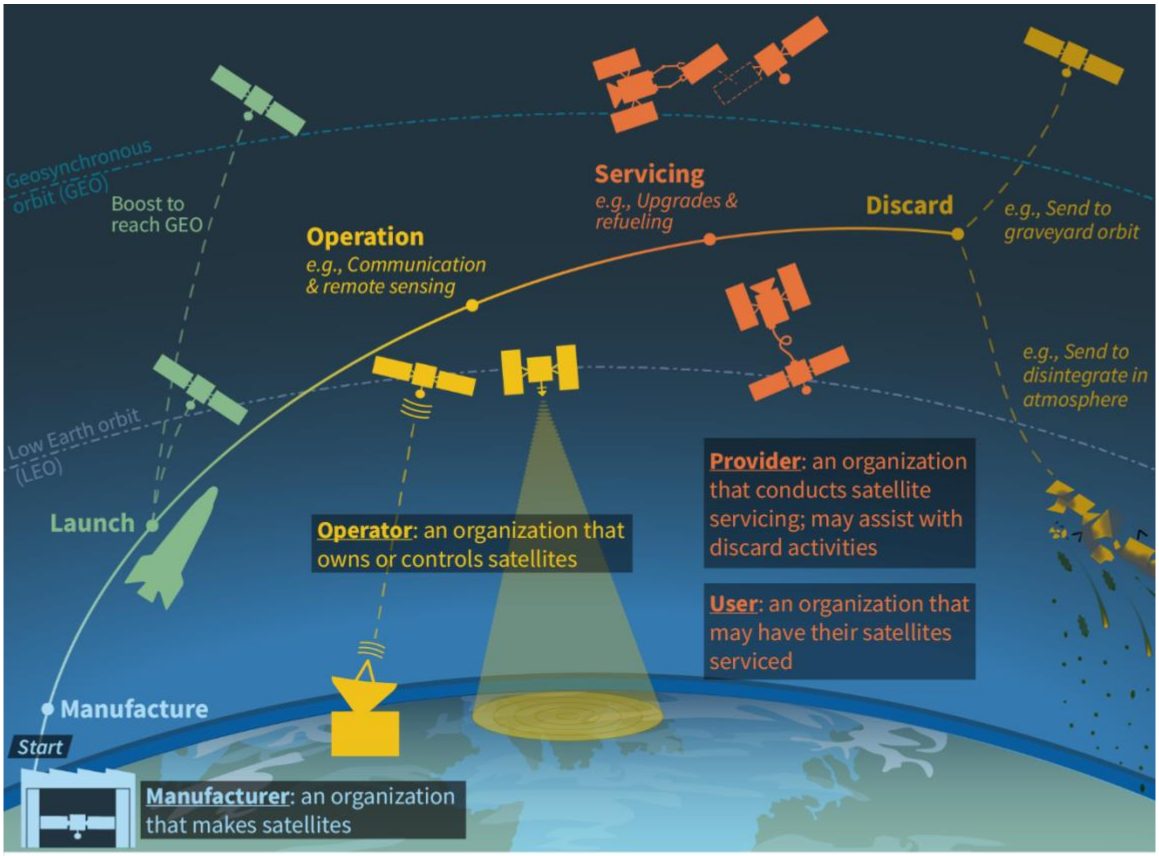
Figure 2: Common orbit categories



Source: GAO (analysis and illustration). | GAO-25-107555

Figure 3 shows the phases of a satellite's lifetime and the entities involved in its servicing, which include satellite operators and providers of ISAM activities.

Figure 3: Roles in satellite servicing



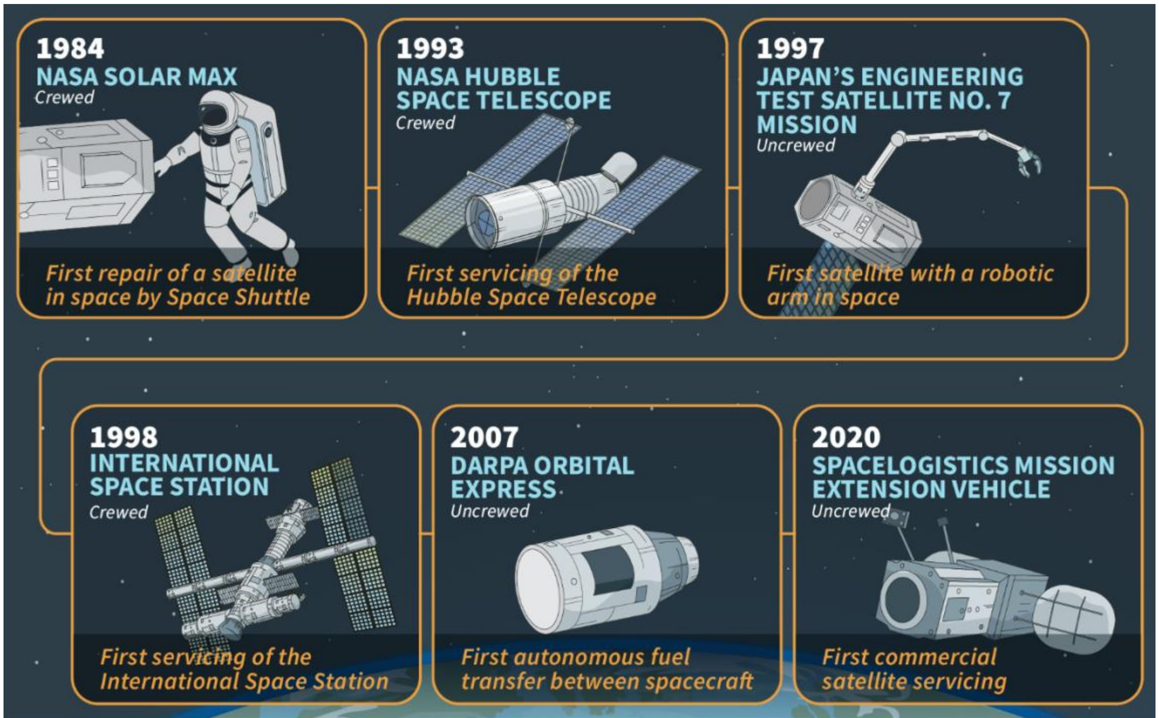
Source: GAO (analysis and illustration). | GAO-25-107555

1.2 Historical ISAM efforts

For more than 40 years, the National Aeronautics and Space Administration (NASA) and other entities have used ISAM capabilities to extend the lifespans of and provide upgrades to spacecraft (see fig. 4). Astronauts performed most of the servicing missions. For example, astronauts repaired or upgraded the Hubble Space Telescope five times between 1993 and 2009. Additionally, astronauts and complex robotics systems assembled the International Space Station beginning in 1998, including connecting large metal truss structures, fluid lines, and electrical wires. Astronauts and robots have installed numerous components onto the station, such as roll-out solar arrays as recently as 2023.

Conversely, uncrewed robotic in-space servicing is not common, though there have been demonstrations and operations over the past few decades. For example, the Defense Advanced Research Projects Agency's (DARPA) Orbital Express mission in 2007 demonstrated that a satellite could robotically refuel and upgrade another satellite—foundational capabilities necessary for automated ISAM. Two U.S. commercial satellites docked robotically with their client satellites and performed uncrewed servicing missions starting in 2020, but no additional operational U.S. servicing satellites have been launched since then.

Figure 4: Selected historical in-space servicing achievements



Source: GAO (analysis and illustration); macrovector/stock.adobe.com (astronaut). | GAO-25-107555

In-space manufacturing has provided the opportunity to create materials and goods for use in space and on Earth. Manufacturing parts on demand in space can simplify logistics for space exploration. Semiconductor crystals grown on the International Space Station demonstrated significant improvement in material properties (e.g., uniformity of structure) compared to crystals grown on Earth.[7] Additionally, private companies are developing and manufacturing pharmaceuticals in space for use on Earth by using new chemical processes that only occur in microgravity conditions.[8]

1.3 Federal government and other roles in ISAM

In 2022, the White House Office of Science and Technology Policy (OSTP) published a national strategy to promote the U.S.

[7]For more information on in-space manufacturing of semiconductor crystals for Earth use, see GAO, *On the Horizon: Three Science and Technology Trends that Could Affect Society,* GAO-25-107542 (Washington, D.C.: Nov. 13, 2024).

[8]Microgravity is the condition in which people or objects appear to be weightless because they are effectively in free fall. The effects of microgravity can be seen when astronauts and objects float in space.

development of ISAM capabilities.[9] The strategy outlines six strategic goals, including advancing ISAM research and development and accelerating the emerging ISAM commercial industry. OSTP also published the National ISAM Implementation Plan in 2022.[10] The implementation plan directs agencies, including the Department of Defense (DOD), NASA, and the Department of Commerce, to lead activities that support the national strategy's goals.[11]

There are many federal agencies involved in ISAM efforts (see fig. 5). NASA and DOD are the primary technology developers and potential users of ISAM capabilities, having spent more than $2 billion developing in-space servicing demonstration missions over the past decade, according to agency documentation and officials.[12] Other agencies—the Federal Aviation Administration (FAA), Federal Communications Commission (FCC), Department of Commerce, and Department of State—regulate ISAM and other commercial space-related activities. Outside of regulatory activities, the Office of Space Commerce is tasked with fostering the growth and advancement of the U.S. commercial space industry.[13]

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[9]Office of Science and Technology Policy, *In-space Servicing, Assembly, and Manufacturing National Strategy* (Washington, D.C.: April 2022).

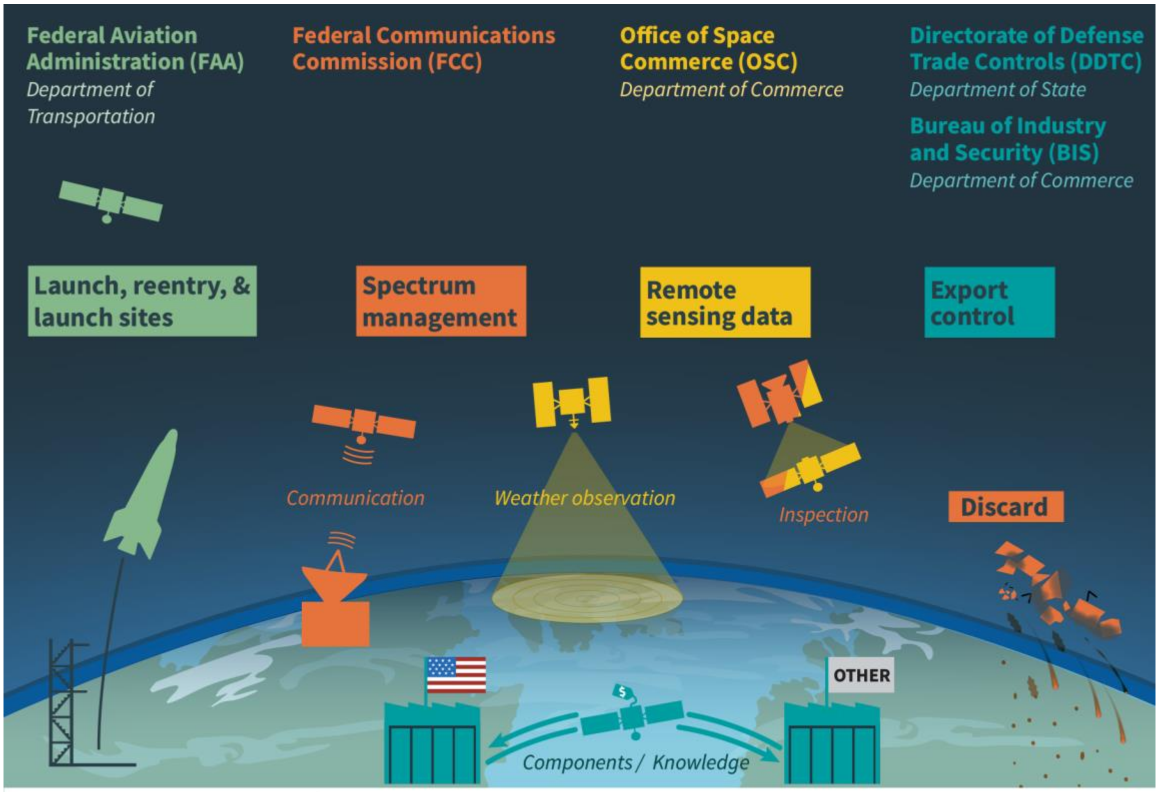
[10]Office of Science and Technology Policy, *National In-space Servicing, Assembly, and Manufacturing Implementation Plan* (Washington, D.C.: December 2022).

[11]The other agencies tasked in the plan are the Office of the Director of National Intelligence, the Department of Education, the Department of Transportation, the Department of State, and the National Science Foundation.

[12]NASA had obligated approximately $1.5 billion for the On-Orbit Servicing, Assembly, and Manufacturing 1 (OSAM-1) project as of January 2024, according to NASA documentation. GAO, *NASA: Assessments of Major Projects,* GAO-25-107591 (Washington, D.C.: July 1, 2025), 16. NASA canceled the OSAM-1 project in 2024. See appendix III for additional information.

[13]The Office of Space Commerce is located within the Department of Commerce's National Oceanic and Atmospheric Administration.

Figure 5: Roles of federal agencies in regulating commercial space activities



Source: GAO (analysis and illustration). | GAO-25-107555

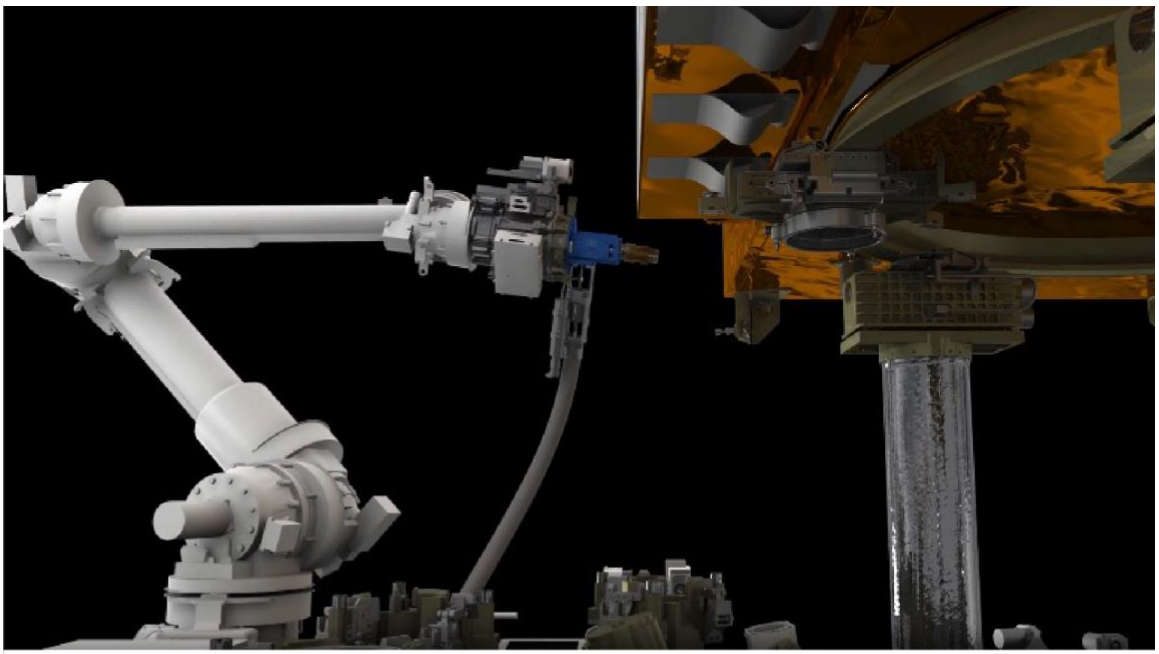
The National ISAM Implementation Plan included the creation in November 2023 of what became the Consortium for Space Mobility and ISAM Capabilities (COSMIC), which the plan tasked with coordinating and promoting the development of domestic ISAM capabilities. COSMIC is funded by NASA but operates independently, with members from the U.S. government, academia, and private industry.

In 2017, DOD's DARPA created the Consortium for Execution of Rendezvous and Servicing Operations (CONFERS), whose goal is to promote satellite servicing to enable the space economy and to develop industry-led recommendations for satellite servicing standards. It became an independent global trade association in 2022, with international membership across industry, academia, research institutions, and government.

2 Potential Benefits of ISAM

ISAM technologies and capabilities could change the paradigm of how spacecraft are designed, built, operated, and discarded. Since the advent of artificial satellites and other spacecraft, almost all have been assembled on Earth and, once in space, sustained themselves with no outside intervention beyond communication. ISAM could change that, potentially delivering benefits like reduced cost, reduced risk, increased flexibility, and an increased ability to address failures after launch. In the future, automated ISAM capabilities might enable entirely new types of activities, such as assembly and manufacturing of structures much larger than any existing spacecraft. For a rendered image of a robotic arm servicing a satellite, see fig. 6.

Figure 6: Rendering of a robotic arm servicing a satellite in space



Source: National Aeronautics and Space Administration. | GAO-25-107555

Potential benefits of servicing. In-space servicing could reduce risk and increase flexibility. Currently, accessing a satellite after launch is generally difficult or prohibitively costly, so small failures or oversights can render a satellite less useful or even nonfunctional. To prevent such failures, satellite manufacturers often must build in redundancies. With in-space servicing, satellites would no longer need to be self-reliant and could adapt to evolving mission needs. Servicing includes a variety of different capabilities, such as inspection, repair, maintenance (including refueling), augmentation, and relocation.

One potential benefit of in-space servicing is anomaly resolution, potentially rescuing a costly mission from failure. Such an anomaly could be the result of an internal malfunction or damage from an external source. For example, an operator that knows its satellite experienced an error could hire a servicing satellite to inspect and help find the potential cause of an error, such as a jammed solar panel. The servicing satellite could then be tasked with repairing the jammed solar panel.

A second potential benefit is life extension of older satellites, which has the potential to save money and reduce the amount of orbital debris. Maintenance activities like refueling could enable satellite operators to conduct additional missions more flexibly with less concern for managing a finite fuel supply. These activities could also include replenishing consumables such as coolants to continue operating sensitive scientific instrumentation. Older satellites could also be augmented by upgrading their scientific instruments to gather more precise data or by installing additional components, such as a propulsion unit (similar to a jetpack) to maintain position and orientation. Upgrading or adding components could be less costly and faster than designing, building, and launching a new satellite.

Life extension of existing satellites can keep them operational longer. They can continue to generate revenue or deliver services, which can mitigate disruptions if there are delays in developing or launching replacement satellites. It would also delay the reentry of existing satellites in LEO and any negative environmental effects associated with reentry and disintegration in the atmosphere, and could avoid the launch and reentry associated with a replacement satellite.[14]

A third potential benefit is the ability to relocate objects in space more efficiently and cost effectively. For example, a servicing satellite could transfer another satellite to a higher altitude, which could consume less fuel overall than launching directly into the higher-altitude orbit. Similarly, being able to move orbital debris could make more space available for new satellites or reduce the risk of collision.[15] Relocation also offers greater flexibility for satellites to accomplish a mission or purpose.

Potential benefits of assembly. In-space assembly could enable spacecraft designs that are more advanced or more optimized for the space environment, such as novel configurations and space structures that would be too large, heavy, or fragile to be launched whole. Experts told us that as much as 80 percent of a satellite's mass is for materials and design features to ensure the whole assembled structure survives launch. Reducing structural mass can reduce cost, allow the launch of more structures in the same rocket, or allow satellites to reach higher orbits.

Potential benefits of manufacturing. In-space manufacturing could enable the production of items for use in space, which would circumvent the cost and logistical challenges of transporting them from Earth. Methods could include 3-D printing, crystallizing,

[14]For details on potential environmental effects from the reentry and disintegration of satellites in the atmosphere, see GAO, *Large Constellations of Satellites: Mitigating Environmental and Other Effects*, GAO-22-105166 (Washington, D.C.: Sept. 29, 2022).

[15]The number of potential collisions between two objects in space generally scales with the square of the number of objects; that is, if the number of objects doubles, the number of potential collisions will quadruple. GAO-22-105166.

welding, and coating of materials. Spacecraft components, surface habitats, food, medicine, and other necessities produced in space could support and enable long-term and deep-space human exploration. Producing items where and when they are needed, such as perishable medicines and support structures for moon and Mars exploration, could make new space missions possible when it would be too expensive or time-consuming to transport those goods from Earth.

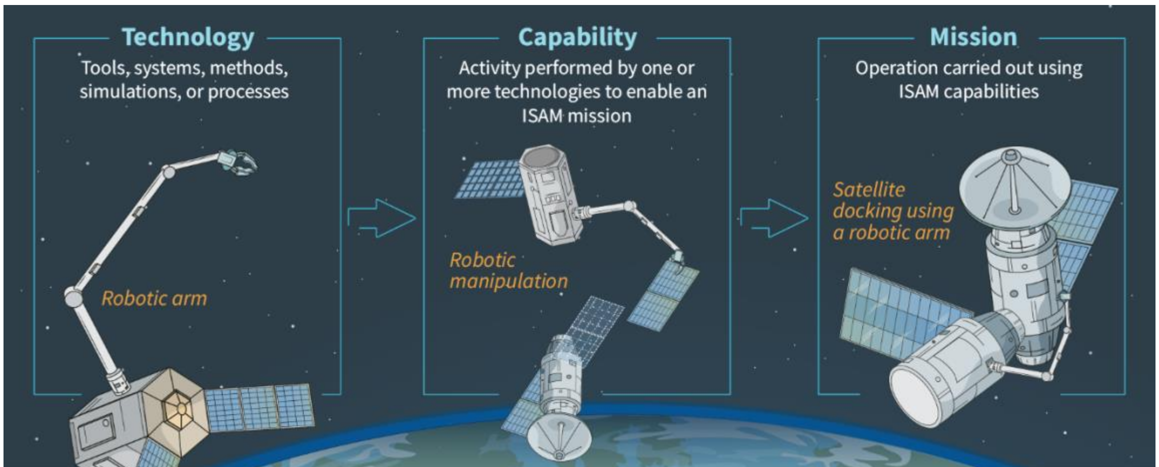
In addition, the microgravity environment of space could provide a manufacturing advantage for products used on Earth. For example, medicines, semiconductors, and fiber optics made in space have more uniform crystal structures, improving their performance compared to those made on Earth.[16]

[16]For more details on the benefits of manufacturing products in space for use on Earth, see GAO, *On the Horizon: Three Science and Technology Trends that Could Affect Society*, GAO-25-107542 (Washington, D.C.: November 2024).

3 Capability Status and Current ISAM Priorities

ISAM is made up of different elements that build on each other, including technologies, capabilities, and missions (see fig. 7).[17]

Figure 7: Definitions of technology, capability, and mission for in-space servicing, assembly, and manufacturing (ISAM)



Source: GAO (analysis and illustration). | GAO-25-107555

The technologies and capabilities that enable servicing are more mature than those that enable assembly and manufacturing because, according to experts, servicing capabilities are a first step toward assembly and manufacturing. Agency officials and experts told us that routine servicing would represent a significant shift from the current state of space activities. But experts also told us the combined benefits of servicing, assembly, and manufacturing capabilities would enable significant steps toward achieving new kinds of missions in space. Government agencies and industry have differing priorities for ISAM technology and capability development based on their different space-related missions.

3.1 Status of capabilities that enable ISAM

NASA compiles the status of ISAM capabilities in its annual *ISAM State of Play* report.[18] The report organizes ISAM activities into 11 capability areas (see table 1). Technologies in almost every area have been used or demonstrated in space, although some are more advanced. In six capability areas,

[17]COSMIC defines seven terms to describe ISAM development and implementation activities: research, technology, function, capability, use case, mission, and mission campaign. Consortium for Space Mobility and In-Space Servicing, Assembly and Manufacturing (ISAM) Capabilities, "COSMIC Lexicon," COSMIC-E02-C013-2024-A (August 2024).

[18]Dale Arney et al., *In-space Servicing, Assembly, and Manufacturing (ISAM) State of Play – 2024 Edition*, National Aeronautics and Space Administration (Oct. 31, 2024).

missions are currently operating with some automation. In two others, the only activities in space have been demonstrations.

Table 1: Capability areas for in-space servicing, assembly, and manufacturing

Capability area	Description	Example	Most advanced use of capability
Inspection	Observing spacecraft and other objects in space to understand their features and status.	Identifying the cause of a spacecraft malfunction.	Used in mission (remotely assisted)
Rendezvous, proximity operations, capture, and docking	Moving two or more spacecraft into proximity, which could include connecting them.	Moving one spacecraft toward another one and then connecting the two.	Used in mission (remotely assisted)
Relocation	Moving a spacecraft into a new orbit or orientation using another spacecraft.	Removing a nonfunctioning spacecraft or orbital debris to a graveyard orbit.	Used in mission (remotely assisted)
Robotic manipulation	Manipulating payloads and spacecraft subsystems using robotic systems.	Cutting wires or bolts with a robotic arm and manipulator.	Used in mission (remotely assisted)
Refueling and fluid transfer	Transferring fuel or other fluid from one spacecraft to another.	Refueling a spacecraft to extend its maneuvering capability.	Used in mission (remotely assisted)
Planned repair, upgrade, maintenance, and installation	Adding, replacing, or removing components on a spacecraft intended to receive those components or have them removed.	Installing new scientific instruments on an upgradeable space telescope.	Used in mission (remotely assisted)
Unplanned or legacy repair and maintenance	Adding, replacing, or removing components on a spacecraft not intended to receive those components or have them removed.	Performing complex operations on a legacy spacecraft, such as upgrading it by cutting off surrounding structures to access and replace components.	Used in mission (astronaut assisted)
Structural manufacturing and assembly	Fabricating or assembling structures in space to create spacecraft components or subsystems.	3-D printing metal structures, such as trusses.	Used in mission (astronaut assisted)

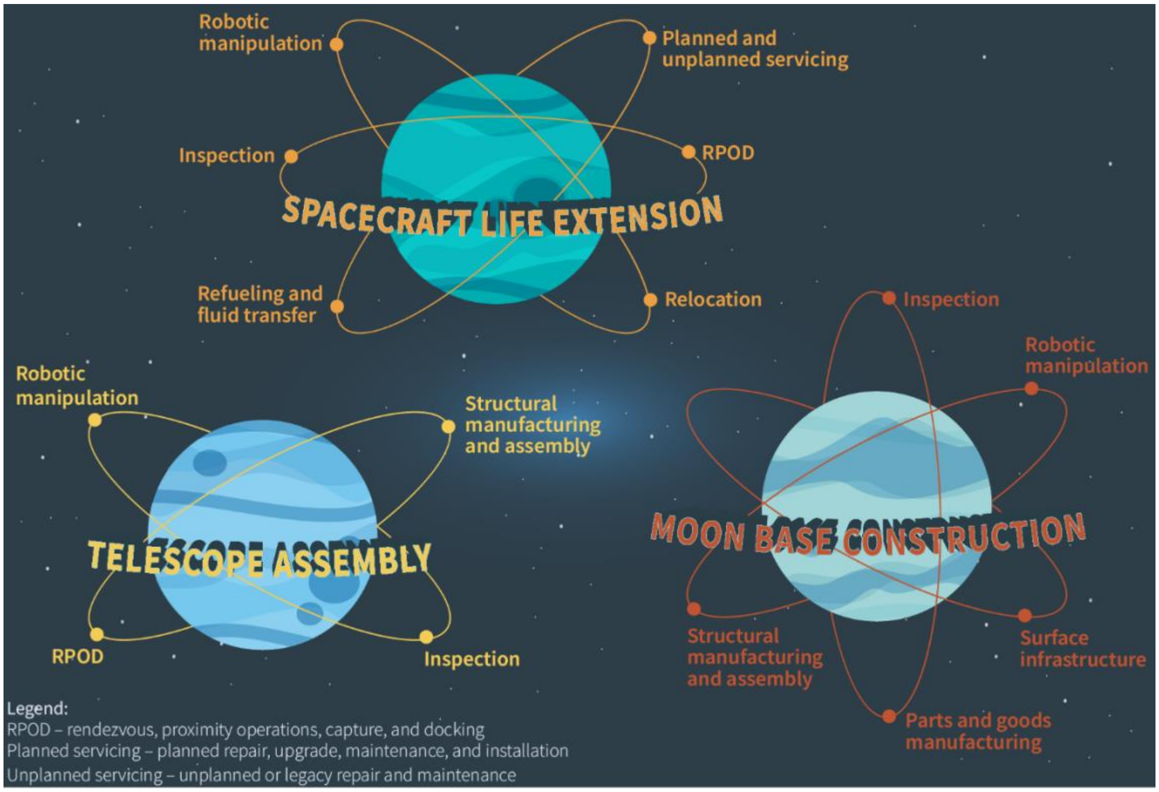
Capability area	Description	Example	Most advanced use of capability
Recycling, reuse, and repurposing	Using components already in space in a new spacecraft or making new components out of materials from defunct spacecraft.	Recycling polymer parts into filament to build new parts as needed.	Demonstrated in space
Parts and goods manufacturing	Producing spare parts, subsystems, and components for use in space, on Earth, or on a lunar or planetary surface.	Manufacturing medicine on an as-needed basis for extended space missions.	Demonstrated in space
Surface infrastructure	Excavating, constructing, and outfitting infrastructure on a planetary surface and the logistics to support operations.	Building a road on the moon.	Not yet demonstrated in space

Source: GAO analysis of NASA's *In-space Servicing, Assembly, and Manufacturing State of Play – 2024 Edition* and agency information. | GAO-25-107555

Note: "Spacecraft" denotes an artificial satellite, space telescope, space station, or deep-space vehicle.

New kinds of space missions, such as spacecraft life extension, robotic in-space telescope assembly, and a permanent presence on the moon, might require support from several capabilities. Some of these capabilities might be consistent across many types of missions, but others might be unique to certain types of missions (see fig. 8).

Figure 8: In-space servicing, assembly, and manufacturing capabilities supporting notional space missions



Source: GAO (analysis and illustration). | GAO-25-107555

3.2 Current and planned ISAM activities

Potential users of ISAM technologies and capabilities, including government agencies and industry, have differing priorities for ISAM technology and capability development based on their different space-related missions.

Sustaining maneuverability and having situational awareness in space are priorities for DOD. To that end, DOD is pursuing augmentation and refueling of GEO satellites in the immediate future, enabling them to maneuver with less concern about consuming fuel that cannot otherwise be replenished. For instance, DARPA's Robotic Servicing of Geosynchronous Satellites (RSGS) is a robotic servicing payload incorporated onto a commercial servicing spacecraft planned for launch in 2026 with capabilities that include augmenting satellites with a commercially-made propulsion module.[19] The U.S. Space Force, the Air Force Research Laboratory, and the Defense Innovation Unit reported pursuing related in-space refueling efforts in partnership with industry to be demonstrated in 2026. Additionally, the Defense Innovation

[19]See appendix III for more details on this and other selected ISAM activities.

Unit reported supporting industry's development of standardized robotic arms and spacecraft that can support a wide range of DOD space missions.

NASA officials are interested in several ISAM technologies and capabilities. The agency developed the On-Orbit Servicing, Assembly, and Manufacturing 1 (OSAM-1) project, which sought to demonstrate using robotic arms to refuel a satellite not designed to be refueled in 2026.[20] However, NASA canceled the project in September 2024 due to continued technical, cost, and schedule challenges along with a broader shift of the ISAM community away from refueling spacecraft not designed to be refueled. Separately, NASA funded the Small Spacecraft Propulsion and Inspection Capability (SSPICY) mission, which would demonstrate commercial capabilities to inspect defunct U.S. satellites beginning in 2027. In addition to satellite servicing, NASA officials said they are potentially interested in upgrades to scientific instruments such as telescopes and other spacecraft. They are researching assembly and manufacturing technologies and capabilities that could help sustain long-term human exploration, including technologies for NASA's Artemis program, which plans to return humans to the moon.

There are several companies actively developing ISAM capabilities, such as inspection, refueling, and relocation, for missions like orbital debris removal. Intended users for these capabilities include both federal government and private companies. Industry satellite operators, such as the communication satellite company Intelsat, are prioritizing near-term satellite servicing. Servicing can augment propulsion capabilities to keep a GEO satellite in the proper orbital position and orientation, so it continues to provide revenue. The private company SpaceLogistics has two Mission Extension Vehicles (MEV)—commercially available propulsion devices in orbit that attach like a jetpack to other satellites. As of April 2025, SpaceLogistics is the only U.S. ISAM provider that has operationally provided servicing to a commercial customer, using the Mission Extension Vehicles to extend the lives of two Intelsat communications satellites and moving one of them to a graveyard orbit before undocking from it.

Appendix III provides additional information on selected U.S. ISAM activities, and appendix IV provides information on selected international ISAM activities.

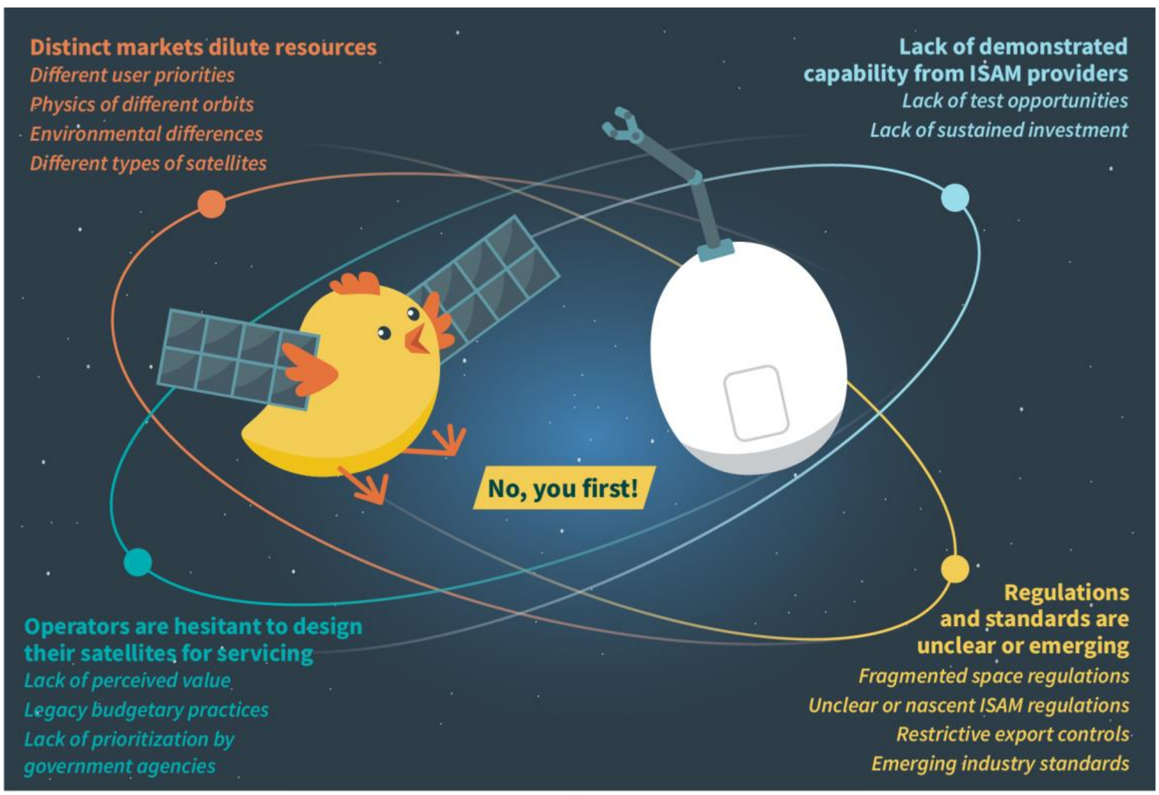
[20]OSAM-1 would have also demonstrated assembly and manufacturing capabilities. In September 2024, NASA requested information on potential partnerships for alternate use cases of the OSAM-1 flight hardware, test facilities, and experienced personnel.

4 Challenges to the Development and Use of ISAM

While activity in the ISAM sector is increasing, continued ISAM development faces challenges. Perhaps most notable is what agency officials and experts called a "chicken-and-egg problem." Satellite operators are hesitant to design satellites to be serviceable (known as "prepared satellites") until commercial servicing capabilities are demonstrated and available. But the potential providers of those services are hesitant to develop the required capabilities until there are enough serviceable satellites to constitute a user base. As a result, each group is waiting for the other to move first. In the meantime, satellites continue to be treated as disposable.

Several different challenges are contributing to this standoff (see fig. 9). The rest of this chapter details those challenges.

Figure 9: Challenges facing the development and use of in-space servicing, assembly, and manufacturing (ISAM)



Source: GAO (analysis and illustration); Elokua/stock.adobe.com (chick). | GAO-25-107555

4.1 Distinct markets dilute resources

The potential ISAM user base is generally divided into distinct markets, both by user priorities and orbits. Though a single servicing product could perform multiple servicing functions (e.g., inspection, robotic manipulation, and refueling), it is likely not possible for that product (e.g., a refueling satellite with one type of fuel) to serve all these markets. Demand is therefore fragmented, diluting the potential payoff for any resources devoted to developing ISAM technologies and capabilities. The following further details this fragmentation.

Different user priorities. Some experts said that user differences fragment the market and reduce the incentive for ISAM providers to develop or fund any particular technology. As described above, government and commercial satellite operators are interested in different ISAM capabilities. Even among those interested in the same capabilities, the market can be divided. For example, DOD satellites primarily use hydrazine as fuel, whereas commercial satellites with electric propulsion systems primarily use krypton or xenon. Providing both on the same servicing satellite could require multiple types of fuel and interfaces, which adds to the complexity and cost of the satellite.[21] An in-space refueling provider may therefore not be able to offer a single technology to serve the entire market.

Physics of different orbits. In the near term, satellites in GEO may be a more appealing servicing market than those in LEO, according to agency officials and experts. GEO satellites are concentrated in a single ring, orbiting in the same direction and at the same altitude above the equator. In contrast, LEO satellites form a multilayer shell, with satellites traveling in many different directions and at different altitudes (see fig. 2). A servicing satellite traveling around GEO would therefore use much less fuel, likely making it more profitable.

Environmental differences. The LEO and GEO operational environments are different, potentially requiring different designs for servicing satellites. For example, because LEO satellites circle the Earth approximately every 90 to 120 minutes, they experience rapid cycles of light and dark that can interfere with sensors. Servicing satellites would have to deal with such issues when approaching and docking. In contrast, because of high radiation in GEO, servicing satellites in that environment may need radiation hardening, which can be costly. A servicer designed for GEO may not function efficiently in LEO, and vice versa.

Different types of satellites. Due to differences in lifespans and costs, GEO satellites may be more worthwhile to service than LEO satellites. GEO satellites are generally more expensive and designed to last longer than LEO satellites. GEO satellites cost around $8,000 per kilogram to launch and are generally designed to last around 14 years. LEO satellites tend to launch for around $3,000 per kilogram and generally have

[21]Agency officials we spoke to described research on "multimode propulsion," where one fuel would be used for both chemical and electric propulsion. If this research is successful and such technology is widely adopted, the challenge to servicing posed by multiple fuels could be reduced.

lifespans of around 4 years.[22] As a result, servicing a GEO satellite may deliver significantly more benefits for a satellite operator, in the form of avoiding or postponing another launch.

For these reasons, GEO represents a more worthwhile market for servicing, according to existing analyses and experts, though particularly large and expensive LEO satellites may also be worth servicing. The only U.S. commercial servicers to successfully complete operational missions thus far, SpaceLogistics's Mission Extension Vehicles, serve GEO satellites, as will their planned follow-on program.

4.2 Operators are hesitant to design their satellites for servicing

Government and commercial operators are hesitant to require their satellites be designed for servicing and thus send a demand signal, for reasons that include the following.

Lack of perceived value. Operators reported that they have not seen sufficient value in requiring satellites to be serviceable and typically do not account for the benefits of serviceability when setting requirements for new satellites.[23] Furthermore, existing studies on the benefits of serviceability are either not publicly available or are too theoretical to be useful when making design choices about any particular satellite. As a result, many operators may view any change that would facilitate servicing as a cost with no associated benefit.

Legacy budgetary practices. According to agency officials, most satellite operators do not have dedicated maintenance budgets, so they do not allocate money for servicing. While some purchasers of ships and aircraft (such as the U.S. Navy) designate budget lines for procurement, operation, and maintenance, agency officials said that satellite operators only have budget lines for procurement and operation. This difference may have arisen because historically there was no practical or economical way to service satellites. As ISAM technology matures, however, the lack of a dedicated maintenance budget means that servicing providers must first persuade potential users to reallocate money to maintenance.

Lack of prioritization by government agencies. While NASA and DOD officials have expressed interest in various ISAM capabilities, agency officials said that the agencies have not pursued operational robotic servicing missions and have not fully committed to requiring their satellites be designed for servicing. NASA recently canceled OSAM-1 and is not requiring the upcoming Nancy Grace Roman Space Telescope to have a port designed for in-space refueling, though it will have some other features intended to facilitate servicing.[24] DOD has not committed to

[22]Price per kilogram estimates are based on published SpaceX launch costs as of January 2024.

[23]Operators estimate costs using equations known as cost estimating relationships, which are based on analysis of the costs of previous missions. Since there have been few successful servicing missions, operators do not have much historical data on servicing. While experts said that there are other benefits of designing satellites for servicing, most operators have not conducted the necessary analysis to incorporate those benefits into the cost estimating relationships.

[24]The Nancy Grace Roman Space Telescope is meeting its serviceability requirements in other ways, such as installing targeting markers, a grapple fixture, and removable insulation

pursuing operational refueling beyond a set of public-private experimental demonstrations involving the Astroscale Prototype Servicer for Refueling (APS-R), Orbit Fab Kamino fuel depot, and the Tetra-5 program, and officials told us that there are no plans for a meaningful service-wide requirement for serviceability. DOD officials we spoke to said that the agency is moving toward using large groups of smaller, shorter lifespan satellites in LEO for many of its missions. This change may cause the agency to prioritize satellite replacement over repair, reducing the DOD need for servicing capabilities.

4.3 Lack of demonstrated capability from ISAM providers

ISAM providers have not established a strong supply of ISAM capabilities for reasons that include the following.

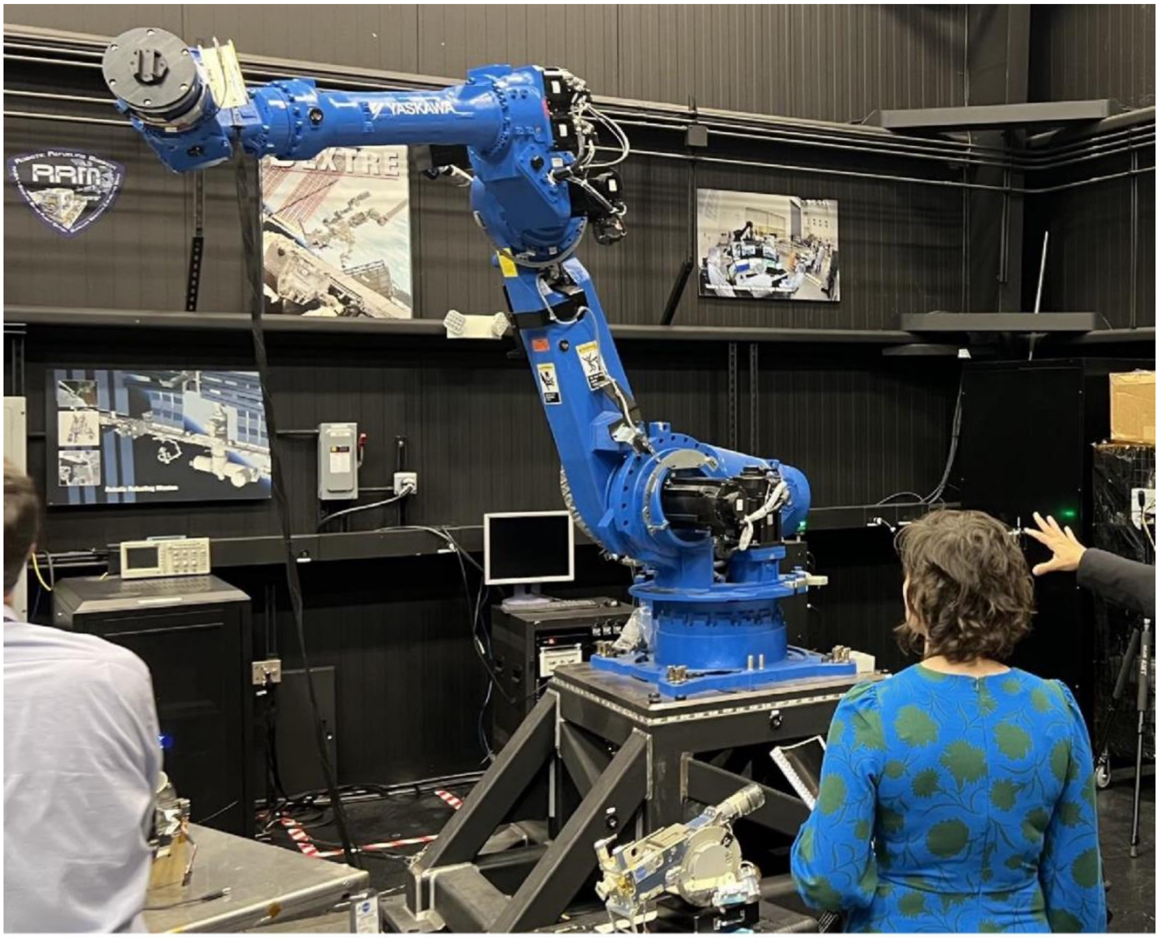
Lack of test opportunities. According to experts, there are too few testing opportunities to develop and demonstrate ISAM technologies, such as on-the-ground test facilities and in-space test beds, particularly for smaller organizations. ISAM providers can use on-the-ground test facilities to simulate aspects of the space environment much more cheaply and quickly than with in-space testing, enabling rapid design and test iterations (see fig. 10). In-space test beds are more representative of the operational environment, and so can be important for advancing the maturity and reducing the perceived risk of using new space technology. Whereas larger companies and government agencies can better afford to build their own test facilities, smaller companies and researchers in academia may have difficulties building or accessing them. To raise awareness of testing opportunities and make them more accessible, NASA catalogs existing federal government and academic ISAM test facilities,[25] and COSMIC is developing a catalog of both government and commercial test facilities.

Lack of sustained investment. Providers of ISAM components and services are largely unable or unwilling to self-fund the large capital costs of development and demonstration. Small providers are particularly vulnerable because, unlike larger providers, they often rely on venture capital and a small number of government contracts, both of which can be unreliable sources of sustained investment. Moreover, providers of in-space robotic arms reported facing international competition, particularly from Canada, where NASA traditionally sources these components.

layers. The Habitable Worlds Observatory, which is still in the pre-formulation phase and not expected to launch until sometime in the 2040s, is expected to be designed for a higher degree of serviceability.

[25]NASA, *In-space Servicing, Assembly, and Manufacturing (ISAM) State of Play - 2024 Edition.*

Figure 10: **A robotic arm used to test a servicing satellite approaching another satellite**



Source: GAO. | GAO-25-107555

4.4 Regulations and standards are unclear or emerging

ISAM regulations and standards lack clarity and are fragmented, resulting in uncertainty and perceived risks for providers and users. The following factors contribute to this situation.

Fragmented space regulations. Commercial spacecraft operators must go through multiple agency approval processes before launching and operating a satellite (see fig. 5), which smaller companies said can be a burden. Agency officials and experts we talked to disagreed as to whether multiple agency approval processes pose a genuine challenge for ISAM activities and whether centralization of authorities should be pursued. Congress and the White House have in the past put forward differing proposals to clarify or centralize the regulatory approval processes, none of which have been adopted.

Unclear or nascent ISAM regulations. Regulations targeted for ISAM are unclear or under development, because almost all satellites currently in orbit were designed to be single use. Traditionally, a satellite was launched, traveled to a single orbit, spent its operational life in that orbit, and then was abandoned or discarded. Policymakers developed existing regulations for this traditional form of space activity. In contrast, satellite servicing could involve moving across multiple different orbits that servicing providers may not have identified when applying for licenses, and then operating near and communicating with other satellites on multiple radio frequency bands. In-space assembly and manufacturing both involve creating satellites or components after launch rather than launching them complete from Earth. Agency officials and experts expressed concern that existing regulations may not be able to easily accommodate such novel activities, which could result in licensing delays and lost revenue opportunities. In 2024, FCC partially addressed such challenges regarding licensing of radio frequency spectrum for servicing providers by finalizing one rule and proposing another.[26] However, these rulemakings would not address all novel activities, such as asteroid mining or deorbiting abandoned debris.

Restrictive export controls. Because of concerns about the potential military applications of certain ISAM technologies, the U.S. government has imposed export controls, which limit the markets available to providers.[27] Some capabilities necessary for ISAM, such as inspection and robotic manipulation of another satellite, could also be used to surveil or interfere with sensitive U.S. government satellites. For this reason, the Export Administration Regulations and the International Traffic in Arms Regulations have historically restricted export of some ISAM technologies. Some servicing providers stated that these export controls restrict their ability to collaborate with international partners and to provide servicing to international users. The Departments of State and Commerce have proposed changes to these export controls to better enable U.S. industry to compete globally while still protecting national security and foreign policy interests.[28]

Emerging industry standards. There are few widely accepted standards for interfaces, such as refueling ports, and other aspects of servicing, which contributes to satellite manufacturers' hesitancy to design satellites for servicing.[29] ISAM is a nascent industry, so standards governing interfaces, performance, and other requirements are not fully developed or adopted. For example, experts told us that satellite manufacturers do not know which refueling port(s) will become the industry norm, and satellite operators may not know how to write design requirements for serviceability. This absence of standards could slow adoption, but developing standards prematurely may hinder

[26]Space Innovation; Facilitating Capabilities for In-Space Servicing, Assembly, and Manufacturing, 89 Fed. Reg. 18,875 (Mar. 15, 2024). *See also*, Assessment and Collection of Space and Earth Station Regulatory Fees for Fiscal Year 2024; Review of the Commission's Assessment and Collection of Regulatory Fees for Fiscal Year 2024, 89 Fed. Reg. 60,572 (July 26, 2024).

[27]Technologies that have both civilian and military applications are referred to as "dual use."

[28]International Traffic in Arms Regulations (ITAR): U.S. Munitions List Categories IV and XV, 89 Fed. Reg. 84,482 (Oct. 23, 2024). Export Administration Regulations: Revisions to Space-Related Export Controls, Including Addition of License Exception Commercial Space Activities (CSA), 89 Fed. Reg. 84,784 (Oct. 23, 2024).

[29]An interface is a component where two different systems interact. For example, the refueling port on a satellite is an interface between the servicing satellite providing fuel and the satellite receiving fuel.

innovation, according to agency officials and experts. As of August 2024, Space Force had designated two refueling port designs as preferred interface standards. As of March 2025, CONFERS, an international consortium, had developed several standards (one of which has been adopted by the International Organization for Standardization and another of which has been adopted by the American Institute of Aeronautics and Astronautics[30]), including standards on approaching another satellite, power and data interfaces, and fluid transfer.

[30]International Organization for Standardization, ISO 24330: *Space systems — Rendezvous and Proximity Operations (RPO) and On Orbit Servicing (OOS) — Programmatic Principles and Practices*, ISO 24330:2022 (July 2022); American Institute of Aeronautics and Astronautics, AIAA S-157-2024: *In-Space Storable Fluid Transfer for Prepared Spacecraft* (March 2025).

5 Policy Options to Help Address Challenges with ISAM Development and Use

We identified five policy options that policymakers—Congress, federal government agencies, academia, the satellite industry (which could include satellite manufacturers, satellite operators, and ISAM providers), standards-setting organizations, and other groups—could consider taking to help address the challenges to the development and use of ISAM technologies and capabilities detailed in chapter 4. This list is not exhaustive but can provide policymakers with a broader base of information for decision-making. For each policy option, we present a table with one or more potential implementation approaches, opportunities the option may present, and some factors to consider. The policy options we identified were:

- Maintaining the status quo
- Evaluating, and potentially promoting, serviceability
- Supporting technology development and testing
- Developing or clarifying regulations and standards
- Designating a government champion

Maintain status quo

Policymakers could choose to maintain the status quo, including sustaining currently planned missions and ISAM community efforts to support the development and use of ISAM (see table 2). NASA, DOD, and several commercial companies have efforts underway to develop ISAM capabilities.

Table 2: Policy option – Maintain status quo

Potential implementation approach	Opportunities	Consideration
Sustain current efforts to address challenges to ISAM development and use. This option could include continuing efforts by industry, the National Aeronautics and Space Administration, and the Department of Defense to demonstrate servicing capabilities, standards development work by the Consortium for Execution of Rendezvous and Servicing Operations, regulatory actions, and coordination activities of the Consortium for Space Mobility and ISAM Capabilities.	Current efforts may address some challenges without additional resources. Resources that would have been allocated to further developing ISAM could be used for other opportunities.	Current efforts are not likely to address all challenges, such as not being able to promptly respond to changing mission needs or satellite failures.

Source: GAO. | GAO-25-107555

Evaluate, and potentially promote, serviceability

Policymakers could address distinct, diluted markets (section 4.1) and the hesitancy to design satellites for servicing (section 4.2) by evaluating opportunities and potentially promoting actions to encourage or require satellite manufacturers to design satellites for servicing (see table 3). Agency officials and experts we spoke to were in broad agreement that the federal government has the potential to “crack the chicken-and-egg problem” by being the first mover.

Table 3: Policy option – Evaluate, and potentially promote, serviceability

Potential implementation approaches	Opportunities	Considerations
A federal agency, federally funded research and development center, a nonprofit organization, or another trusted entity could conduct a series of economic studies, including cost-benefit assessments, to identify which satellites would benefit from being designed for servicing. *For example, the National Aeronautics and Space Administration, the Department of Defense, or a trusted third party, such as The Aerospace Corporation or National Academies, could conduct these studies.*	Could make the potential market opportunities and return on investment of satellite serviceability clear to manufacturers and operators. Could help servicing providers identify users and prioritize their development efforts. Could help inform decisions about which other policy options to pursue. Studying the environmental effects of the reentry and disintegration of single-use satellites might reveal further benefits for servicing.	Historical data may not be sufficient to generate reliable evaluations. Some benefits of satellite servicing may not be easily quantifiable. The findings of the studies may not persuade servicing providers or satellite operators to move forward with satellite serviceability. Conducting additional studies rather than directly pursuing development of ISAM capabilities could allow foreign nations to gain a technological advantage.
Government and private satellite operators and manufacturers could update programmatic processes that might be inhibiting the adoption of satellites designed for servicing. *For example, satellite operators could establish a dedicated maintenance and sustainment budget or update cost models to account for the benefits of serviceability.*	Updated programmatic processes could help account for benefits and show the true costs of servicing versus deploying new satellites.	Some changes, such as updating cost models, may depend on the results of the studies discussed above.

Potential implementation approaches	Opportunities	Considerations
Government and private satellite operators and manufacturers could require their satellites to be designed for servicing. *For example, satellites could include relatively lower-cost components that facilitate servicing, such as targeting markers, grapple fixtures, and removable insulation layers.*	Could establish a clear user base, incentivizing servicing providers. Could be relatively inexpensive compared to the overall cost of a satellite.	Such requirements may specify a particular interface, which may limit the pool of available servicing providers. If only a small number of satellite operators and manufacturers implement such requirements, servicing providers may not be sufficiently incentivized.
Congress or government regulators could require certain categories of satellites to be designed for servicing as part of U.S. licensing requirements.	Could establish a clear user base, incentivizing servicing providers. Relatively inexpensive compared to the overall cost of a satellite.	Regulators may lack the authority to require serviceability and may not have jurisdiction of satellites owned or licensed outside of the U.S. Such requirements may specify a particular interface, which may limit the pool of available servicing providers.
Government agencies could require some or all of their satellites and those of their contractors to be designed for servicing.	Could establish a clear user base, incentivizing servicing providers. Could provide a push for the commercial market to design their satellites to be serviceable. Relatively inexpensive compared to the overall cost of a satellite. Would not require a legislative mandate to implement.	This approach would only cover a subset of the market. Such requirements may specify a particular interface, which may limit the pool of available servicing providers.

Source: GAO. | GAO-25-107555

Support technology development and testing

Policymakers could address the lack of demonstrated capability from providers (section 4.3) by supporting efforts to test ISAM technologies (see table 4). Agency officials and experts we spoke with were in broad agreement that the federal government has a key role to play in supporting the infrastructure and demonstrations necessary for the development of ISAM technologies.

Table 4: Policy option – Support technology development and testing

Potential implementation approaches	Opportunities	Considerations
The ISAM community (including government, industry, and academia) could make on-the-ground test facilities more accessible and, if necessary, create new test facilities. *For example, the community could expand existing catalogs of test facilities. Companies could build facilities to meet specific needs, as Space Dynamics Laboratory is doing for rendezvous, proximity operations, and docking technologies.*	Could enable smaller companies and academic research groups to participate in developing ISAM capabilities. Leveraging existing facilities minimizes the new investment required. Could help recruit and train an ISAM workforce.	On-the-ground tests are considered less representative than in-space tests and would not guarantee adoption by users. Making some test facilities more accessible may introduce security concerns. Establishing new test facilities could be expensive.
Government agencies and private companies could support the creation of and access to an in-space test bed for ISAM technologies. *For example, federal agencies could make a system like RSGS or OSAM-1 available to companies and research groups to test new algorithms and procedures in space.*	Could reduce technical risk, satisfy many potential users, and encourage adoption. Could enable smaller organizations to demonstrate their products. Could help recruit and train an ISAM workforce.	Resources dedicated to such a test bed would be unavailable for other agency or company priorities. Demonstrations would not guarantee adoption by users.
Government agencies and private companies could support a series of in-space missions to demonstrate life extension, refueling, debris removal, or other capabilities.	Could reduce technical risk, satisfy many potential users, and encourage adoption. Could align technology development, test resources, and regulatory changes.	Resources used would be unavailable for other priorities. Demonstrations would not guarantee adoption.

OSAM-1: On-Orbit Servicing, Assembly, and Manufacturing 1
RSGS: Robotic Servicing of Geosynchronous Satellites
Source: GAO. | GAO-25-107555

Develop or clarify regulations and standards

Policymakers could address unclear and emerging regulations and standards (section 4.4) by developing or clarifying regulations and standards (see table 5). Agency officials and experts we spoke to disagreed about the timeliness and necessity of standards and regulations.

Table 5: Policy option – Develop or clarify regulations and standards

Potential implementation approaches	Opportunities	Considerations
Government regulators could clarify ISAM regulations and licensing processes, including for access to radio spectrum. *For example, FCC has proposed rules that could reduce licensing hurdles, although the proposal does not address the lack of radio-spectrum availability.*	Could help enable ISAM providers to serve users and encourage additional investment. Dedicated or prioritized radio spectrum could enable safe and reliable ISAM operations.	The ISAM industry is still developing, and regulations may inadvertently create unnecessary barriers to developing technologies. Agencies may not be prepared to promulgate regulations.
The Departments of State and Commerce could continue reevaluating export controls on ISAM technologies. *For example, the Departments of State and Commerce recently proposed loosening export control restrictions on a variety of ISAM technologies.*	Could enable ISAM providers of both services and components to access a larger user base.	Relaxing export controls may pose national security risks. Relaxing export controls may not address all factors that inhibit international collaboration.
Congress could designate a centralized licensing authority for all commercial space activities.	Could lower barriers for ISAM providers to serve users and encourage additional investment in ISAM technologies.	It may be difficult to achieve consensus on which agency should have the authority. A centralized licensing authority may still need to coordinate with other agencies, reducing the benefits of centralization.
Government agencies, nonprofit organizations, standards organizations, and private industry could develop and promulgate standards. *For example, CONFERS could continue its effort to develop ISAM-related standards.*	Could reduce uncertainty for ISAM providers and satellite operators, encouraging them to specify that their satellites be designed for servicing.	The ISAM industry is still nascent, and promulgating standards at an early stage may constrain innovation.

Potential implementation approaches	Opportunities	Considerations
Government satellite manufacturers and operators could specify what standard(s) they will accept. *For example, they could follow the example of the U.S. Space Force, which designated two types of refueling ports as accepted interfaces.*	Could establish a clear user base, incentivizing servicing providers.	Some government agencies may not be prepared to select a standard for future operations.

CONFERS: Consortium for Execution of Rendezvous and Servicing Operations
FCC: Federal Communications Commission
Source: GAO. | GAO-25-107555

Designate a government champion

Policymakers could address the challenges we identified by designating a government champion to support ISAM and help implement any of the other policy options (see table 6). U.S. government ISAM activities are dispersed across numerous agencies and components. OSTP sought to coordinate ISAM activities via the ISAM National Strategy and National ISAM Implementation Plan, but agency officials and experts told us that agencies have made little progress to fulfill the plan beyond the creation of COSMIC. Agency officials and experts generally said that a champion with proper resources and authority could advance ISAM development and adoption, but experts also expressed concern that the interests of federal agencies are diverse enough to inhibit such coordination.

Table 6: Policy option – Designate a government champion

Potential implementation approach	Opportunity	Consideration
Congress or the White House could designate a government champion to support ISAM development and coordinate with the Consortium for Space Mobility and ISAM Capabilities.	The government champion could oversee and coordinate activities described in the ISAM National Strategy and the National ISAM Implementation Plan, and the policy options identified in this report.	A government champion without sufficient authority, resources, and clear direction could be ineffective and wasteful.

Source: GAO. | GAO-25-107555

6 Agency and Expert Comments

We provided a draft of this report to the Department of Commerce, DOD, FCC, NASA, OSTP, and the Department of State for review and comments. DOD and NASA provided technical comments, which we incorporated as appropriate. The Department of Commerce, FCC, OSTP, and the Department of State reviewed the report and had no technical comments.

We also offered our expert meeting participants the opportunity to review and comment on a draft of this report, consistent with previous technology assessment methodologies. Fifteen of those experts reviewed our draft report; we incorporated their comments as appropriate.

We are sending copies of this report to the appropriate congressional committees, the Secretary of Commerce, Secretary of Defense, the Chairman of FCC, the Acting Administrator of NASA, the Director of OSTP, the Secretary of State, and other interested parties. In addition, the report is available at no charge on the GAO website at https://www.gao.gov/.

If you or your staff have any questions about this report, please contact me at HowardK@gao.gov. Contact points for our Offices of Congressional Relations and Public Affairs may be found on the last page of this report. GAO staff who made key contributions to this report are listed in appendix V.

//signed//

Karen L. Howard, PhD
Director
Science, Technology Assessment, and Analytics

List of Addressees

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Appendix I: Objectives, Scope, and Methodology

Objectives

We prepared this report at the initiative of the Comptroller General to assist Congress with its oversight responsibilities, in light of the evolving space environment, including the rapid increase in the number of satellites as government agencies and commercial entities seek to expand the amount and variety of in-space activities. Specifically, we focused on in-space servicing, assembly, and manufacturing (ISAM). For this report, we described the potential benefits and status of capabilities available or in development for ISAM, described challenges of developing or using these capabilities, and identified options that policymakers could consider that could help realize benefits or address challenges.

Scope

We limited the scope of this technology assessment to ISAM activities that include some degree of autonomous operations and do not require a human in space. We also scoped primarily to U.S. projects, companies, and policies. We primarily focused on technologies and capabilities for servicing, because they are more mature than those directly supporting assembly or manufacturing. While we considered current and potential military and intelligence uses of ISAM technologies and capabilities, we excluded sensitive and classified information.

Methodology

For all objectives, we reviewed literature and agency documents; interviewed a variety of agency officials, industry representatives, and other stakeholders; attended conferences and workshops; and convened a meeting of experts. For objective 3 (in addition to the steps above), we identified five policy options, including the status quo.

Review of literature and documents

For all objectives, we reviewed relevant literature and documents identified by agency officials, stakeholders, and our literature search. A GAO librarian conducted a background literature search to find articles on ISAM technology, research, and policies, using databases such as ProQuest, EBSCO, Scopus, Dialog Aerospace & Defense Collection, Janes, LexisNexis, Harvard Think Tank Search, and IEEE Xplore. We narrowed our search to include articles published since 2019 to capture recent development in ISAM. Results of the search included scholarly or peer-reviewed material; government reports; trade or industry papers; and association, nonprofit, and think-tank publications. We selected articles most relevant to our objectives for further review.

The literature and documents provided information and knowledge for our understanding of the state of ISAM technology, helped us identify expert individuals or groups to interview or consider for the meeting of experts, and provided additional context for what we heard during the interviews. In addition to our search, we received literature and documents from agency officials, industry representatives, other stakeholders we interviewed, and the participants in our expert meeting. We excluded sensitive and classified information from our report.

Interviews and site visits

For all objectives, we conducted semi-structured interviews focused on the different ISAM technologies and capabilities, how those technologies and capabilities may develop in the coming years, the potential benefits and challenges of developing and using these technologies and capabilities, and policy options that could help realize benefits or address challenges. We tailored some of the interview questions based on the interviewees' roles, responsibilities, and expertise. We identified groups or individuals to interview who had relevant expertise in these areas through our review of background literature and from recommendations from other interviewees. We selected our interviewees to complement the other parts of our methodology, such as verifying key information from literature and documents and supplementing the views provided by our expert participants. In our report, we refer to individuals representing an agency as "agency officials," and individuals who participated in our expert meeting or were interviewed as "experts."

We interviewed federal officials at the agencies primarily involved with supporting or regulating ISAM activities, including senior-level officials or technical experts from the Department of Defense (DOD), Department of State, Federal Communications Commission (FCC), National Aeronautics and Space Administration (NASA), National Oceanic and Atmospheric Administration (NOAA), and Office of Science and Technology Policy (OSTP). The National Space Council did not respond to our requests between July 2024 and early January 2025 for an interview. We did not interview or seek to interview officials in the U.S. intelligence community.

We also interviewed industry representatives from trade associations that represent the ISAM industry, providers of ISAM technologies and their underlying components, satellite operators that are current or potential users of ISAM capabilities, and other companies based on the relevance of their activities to our scope. We interviewed several officials at multiple federally funded research and development centers and at a university affiliated research center, who are actively involved in developing ISAM technologies and policy.

We conducted 12 of these interviews in person as part of site visits to observe test facilities and ISAM technologies under development. Because we interviewed and visited a nongeneralizable sample of stakeholders, the results of our interviews and site visits are illustrative and represent important perspectives but are not generalizable.

Conferences and workshops

To inform all objectives, we attended the 7th Annual Global Satellite Servicing Forum & Exhibition, a conference organized by the Consortium for Execution of Rendezvous and Servicing Operations (an international standards-developing body for ISAM) and the Space Logistics Conference in 2024. We also attended several in-person and virtual events on a variety of ISAM-related topics organized by the Consortium for Space Mobility and ISAM Capabilities (COSMIC), a U.S. coalition of government agencies, private companies, and academic research groups.

Meeting of experts

We convened a 2-day, virtual expert meeting to help provide additional context and information for the evidence we obtained from literature, documents, and interviews; facilitate discussion of the potential benefits and challenges of developing and using ISAM technologies; develop policy options; and discuss opportunities and considerations of the policy options. We divided the meeting into moderated session topics, including life extension and refueling; the future of servicing, assembly, and manufacturing; and crosscutting effects or competing concerns. For each of the session topics, the experts were asked open-ended questions, such as the current state of technologies, the primary challenges facing the deployment of those technologies, and actions that policymakers could take. Prior to the meeting, we asked the experts to provide responses about the primary challenges facing the ISAM sector and what actions could be taken to understand or mitigate those challenges. We used these responses to guide the meeting and to discuss common themes across different kinds of ISAM technologies.

The meeting included a nongeneralizable group of 20 experts from government agencies, industry, academia, and federally funded research and development centers. The experts and their titles and affiliations are listed in appendix II. Based on the session topics, a literature review, interviews, and other prior evidence collection, we identified potential national and international experts. We then selected the experts based on their technical, legal, business, or policy expertise so that the group would include a balanced and diverse set of views from government, nongovernmental organizations, industry representatives, and academic researchers. Prior to the meeting, we asked the experts to identify any potential conflicts of interest, which we considered to be any current financial or other interest that might conflict with the service of an individual because it could (1) impair objectivity or (2) create an unfair advantage for any person or organization. We determined the 20 experts to be free of reported conflicts of interest, except those that were outside the scope of the meeting or where the overall design of our meeting and methodology was sufficient to address them for our purpose. We also judged the group as a whole to have no inappropriate biases for our purpose. The comments of these experts generally represented their individual views and not the organizations with which they were affiliated and are not generalizable to the views of others in the field.

The meeting was professionally transcribed to ensure that we accurately captured the experts' statements. Following the meeting, we continued to draw on the expertise of those individuals who agreed to work with us during the remainder of our study, as explained further in appendix II. We provided the experts an opportunity to provide feedback on potential policy options and implementation approaches. We provided the experts an opportunity to review a draft of our report and provide technical comments, which we incorporated as appropriate.

Policy options

We intend policy options to provide policymakers with a broader base of information for decision-making.[31] The policy options are neither recommendations to federal agencies nor matters for congressional consideration. They are not listed in any specific rank or order. We are not suggesting that they be done individually or combined in any particular way. We have not assessed these options for their feasibility or cost effectiveness. Additionally, we did not conduct work to assess how effective the options may be and express no view regarding the extent to which legal changes would be needed to implement them.

We developed five policy options, with possible implementation approaches, that policymakers could take to help address identified challenges to the deployment and use of ISAM technologies and capabilities. From literature and documents; interviews with federal agency officials, industry representatives, and other technical experts; and the meeting of experts, we identified, selected, and grouped sets of challenges to developing and using ISAM technologies and capabilities. We identified those policy options from literature, documents, interviews, and the meeting of experts that could help address these challenges. We similarly identified examples of implementation approaches under each policy option and present potential opportunities and considerations of implementing each approach.

Quality assurance

We conducted our work from April 2024 to July 2025 in accordance with all sections of GAO's Quality Assurance Framework that are relevant to technology assessments. The framework requires that we plan and perform the engagement to obtain sufficient and appropriate evidence to meet our stated objectives and to discuss any limitations to our work. We believe that the information and data obtained, and the analysis conducted, provide a reasonable basis for any findings and conclusions in this product.

[31] Policymakers is a broad term including, for example, Congress, federal agencies, state and local governments, academic and research institutions, and industry.

Appendix II: Expert Participation

On October 22 and 24, 2024, we convened a meeting of experts to inform our work on in-space servicing, assembly, and manufacturing technologies. The experts who participated in these discussions are listed below, along with their titles at the time of the meeting. Some of these experts provided additional assistance throughout our work, including by sending material for our review or participating in interviews. In addition, 11 experts provided feedback on an early iteration of policy options. Fifteen experts reviewed our draft report, and we incorporated their technical comments as appropriate.

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Appendix III: Selected U.S. ISAM Activities

Figure 11 shows the in-space servicing, assembly, and manufacturing (ISAM) capability areas of select U.S. activities from industry, the National Aeronautics and Space Administration (NASA), and the Department of Defense (DOD). The following pages contain more details on each activity, including a mission summary, a checklist identifying applicable ISAM capability areas, and a timeline of key events. See section 3.1 for additional details on the ISAM capability areas.

Figure 11: Capability areas of selected U.S. ISAM activities

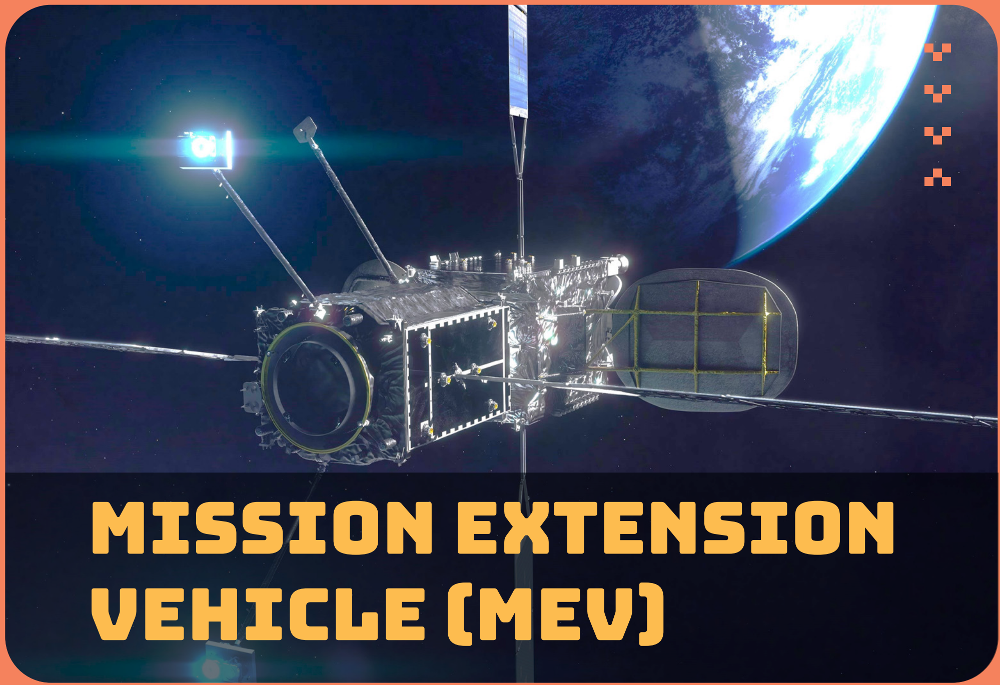
ISAM CAPABILITY AREAS:	ISAM ACTIVITY: MEV	OSAM-1 (CANCELED)	RSGS	TETRA-5
INSPECTION		X	X	X
RENDEZVOUS, PROXIMITY OPERATIONS, CAPTURE, AND DOCKING	X	X	X	X
RELOCATION	X	X	X	
ROBOTIC MANIPULATION		X	X	
REFUELING AND FLUID TRANSFER		X		X
PLANNED REPAIR, UPGRADE, MAINTENANCE, AND INSTALLATION			X	
UNPLANNED OR LEGACY REPAIR AND MAINTENANCE		X	X	
STRUCTURAL MANUFACTURING AND ASSEMBLY		X		
RECYCLING, REUSE, AND REPURPOSING				
PARTS AND GOODS MANUFACTURING				
SURFACE INFRASTRUCTURE				

LEGEND: ISAM – In-Space Servicing, Assembly, and Manufacturing, MEV – Mission Extension Vehicle, OSAM-1 – On-Orbit Servicing, Assembly, and Manufacturing 1, RSGS – Robotic Servicing of Geosynchronous Satellites

Source: GAO analysis of literature (data); Northrop Grumman (MEV), Mike Guinto/NASA (OSAM-1), U.S. Naval Research Laboratory (RSGS), aapsky/stock.adobe.com (satellite render). | GAO-25-107555

ISAM

IN-SPACE SERVICING, ASSEMBLY, AND MANUFACTURING: BENEFITS, CHALLENGES, AND POLICY OPTIONS



Source: Northrop Grumman. | GAO-25-107555

ISAM CAPABILITY AREAS

- INSPECTION
- RENDEZVOUS, PROXIMITY OPERATIONS, CAPTURE, AND DOCKING
- RELOCATION
- ROBOTIC MANIPULATION
- REFUELING AND FLUID TRANSFER
- PLANNED REPAIR, UPGRADE, MAINTENANCE, AND INSTALLATION
- UNPLANNED OR LEGACY REPAIR AND MAINTENANCE
- STRUCTURAL MANUFACTURING AND ASSEMBLY
- RECYCLING, REUSE, AND REPURPOSING
- PARTS AND GOODS MANUFACTURING
- SURFACE INFRASTRUCTURE

MISSION OVERVIEW

The MEV is the first commercial satellite life extension vehicle, designed to provide relocation services to satellites in geosynchronous orbit (GEO). Once connected to its client satellite, MEV uses its own thrusters and fuel supply to extend the satellite's lifetime by maintaining its proper position and orientation in orbit. When the customer no longer desires MEV's service, the MEV can undock and move on to the next client satellite. MEV was developed by SpaceLogistics, a subsidiary of Northrop Grumman, which has deployed two MEV spacecraft.

KEY EVENT TIMELINE

2020	2021	2025	2030
MEV-1 docks with first Intelsat satellite	MEV-2 docks with second Intelsat satellite	MEV-1 discard of docked satellite then servicing of a new satellite	Planned end of MEV-2 relocation services for docked satellite

Source: GAO. (Icons, layout, page elements). | GAO-25-107555

ISAM

IN-SPACE SERVICING, ASSEMBLY, AND MANUFACTURING: BENEFITS, CHALLENGES, AND POLICY OPTIONS

ON-ORBIT SERVICING, ASSEMBLY, AND MANUFACTURING 1 (OSAM-1)

-- CANCELED --

Source: Mike Guinto/NASA. | GAO-25-107555

ISAM CAPABILITY AREAS

- INSPECTION
- RENDEZVOUS, PROXIMITY OPERATIONS, CAPTURE, AND DOCKING
- RELOCATION
- ROBOTIC MANIPULATION
- REFUELING AND FLUID TRANSFER
- PLANNED REPAIR, UPGRADE, MAINTENANCE, AND INSTALLATION
- UNPLANNED OR LEGACY REPAIR AND MAINTENANCE
- STRUCTURAL MANUFACTURING AND ASSEMBLY
- RECYCLING, REUSE, AND REPURPOSING
- PARTS AND GOODS MANUFACTURING
- SURFACE INFRASTRUCTURE

Source: GAO. (Icons, layout, page elements). | GAO-25-107555

MISSION OVERVIEW

The OSAM-1 project was intended to demonstrate a capability to autonomously service satellites in low Earth orbit (LEO) that were not designed to be serviced. NASA planned to transfer OSAM-1 technologies to commercial entities as well. Specifically, OSAM-1 planned to autonomously refuel the U.S. Geological Survey's Landsat 7 satellite. The project also planned to use the Space Infrastructure Dexterous Robot (SPIDER) payload, manufactured by Maxar, to demonstrate on-orbit assembly and installation of an antenna. NASA canceled the project in 2024 due to schedule delays, increasing costs, and technical challenges, along with a broader shift of the ISAM community away from refueling spacecraft not designed to be refueled. In September 2024, NASA released a request for information (RFI) on alternative uses for OSAM-1 technology, facilities, and personnel.

KEY EVENT TIMELINE

2016	2024	2024	2026
Project start	Project cancellation	RFI for alternative uses	Planned launch *(at time of cancellation)*

IS AM

IN-SPACE SERVICING, ASSEMBLY, AND MANUFACTURING: BENEFITS, CHALLENGES, AND POLICY OPTIONS

ROBOTIC SERVICING OF GEOSYNCHRONOUS SATELLITES (RSGS)

Source: U.S. Naval Research Laboratory. | GAO-25-107555

ISAM CAPABILITY AREAS

- INSPECTION
- RENDEZVOUS, PROXIMITY OPERATIONS, CAPTURE, AND DOCKING
- RELOCATION
- ROBOTIC MANIPULATION
- REFUELING AND FLUID TRANSFER
- PLANNED REPAIR, UPGRADE, MAINTENANCE, AND INSTALLATION
- UNPLANNED OR LEGACY REPAIR AND MAINTENANCE
- STRUCTURAL MANUFACTURING AND ASSEMBLY
- RECYCLING, REUSE, AND REPURPOSING
- PARTS AND GOODS MANUFACTURING
- SURFACE INFRASTRUCTURE

MISSION OVERVIEW

The Defense Advanced Research Projects Agency (DARPA) RSGS program will demonstrate robotic servicing of satellites within geosynchronous orbit (GEO). The module with two robotic arms was developed by DARPA and the U.S. Naval Research Laboratory and was incorporated onto the Mission Robotic Vehicle (MRV) developed by SpaceLogistics, a subsidiary of Northrop Grumman. The RSGS program intends to demonstrate robotic servicing, among other missions, across several years.

KEY EVENT TIMELINE

2016	2024	2026
Program start	DARPA robotics module incorporated with MRV	Planned launch

Source: GAO. (Icons, layout, page elements). | GAO-25-107555

ISAM

IN-SPACE SERVICING, ASSEMBLY, AND MANUFACTURING: BENEFITS, CHALLENGES, AND POLICY OPTIONS

Artist rendering of two satellites

Source: aapsky/stock.adobe.com | GAO-25-107555

ISAM CAPABILITY AREAS

- ☒ INSPECTION
- ☒ RENDEZVOUS, PROXIMITY OPERATIONS, CAPTURE, AND DOCKING
- ☐ RELOCATION
- ☐ ROBOTIC MANIPULATION
- ☒ REFUELING AND FLUID TRANSFER
- ☐ PLANNED REPAIR, UPGRADE, MAINTENANCE, AND INSTALLATION
- ☐ UNPLANNED OR LEGACY REPAIR AND MAINTENANCE
- ☐ STRUCTURAL MANUFACTURING AND ASSEMBLY
- ☐ RECYCLING, REUSE, AND REPURPOSING
- ☐ PARTS AND GOODS MANUFACTURING
- ☐ SURFACE INFRASTRUCTURE

MISSION OVERVIEW

Tetra-5 is a DOD program aiming to demonstrate in-space docking and refueling between satellites using a commercial Orbit Fab spacecraft acting as a fuel depot and an Astroscale U.S. spacecraft acting as a fuel shuttle. The program plans to develop two refuelable geosynchronous orbit (GEO) satellites that will also demonstrate autonomous inspection of client satellites for servicing and troubleshooting. Orion Space Solutions, a contract recipient, has completed critical design review (CDR) for the program, which was the last step in design before producing the two satellites.

KEY EVENT TIMELINE

2022	2022	2024	2026
Program start	Contract with Orion Space Solutions	Orion Space Solutions completes CDR	Planned launch

Source: GAO. (all icons, layout, page elements). | GAO-25-107555

Appendix IV: Selected International ISAM Activities

In addition to the U.S., other countries and international entities are developing and demonstrating in-space servicing, assembly, and manufacturing (ISAM) capabilities. The following are examples from the public domain:

- **China** has been reported to have conducted a series of missions to practice on-orbit inspections, robotic arm manipulations, rendezvous, and proximity operations since 2010. Shijian-21 launched in 2021, docked with a defunct satellite, and towed it thousands of kilometers beyond geosynchronous orbit. A recent servicing mission, Shijian-25, launched in January 2025 to test in-space refueling and mission extension technologies. Shijian-21 and Shijian-25 were observed to approach each other in June 2025.
- **Japan** is exploring orbital debris removal. Astroscale Japan's satellite successfully approached and observed a large piece of debris in November 2024. A future mission in development plans to have another satellite capture and deorbit the debris.
- **The European Union** has funded multiple European companies and organizations for the European Robotic Orbital Support Services program, which plans to demonstrate satellite servicing as early as 2026. The program's goal is to develop space vehicles for tasks like in-space inspection and robotic maintenance.
- **The United Kingdom** has funded companies to design missions to remove space debris in low Earth orbit. It has also funded feasibility studies to demonstrate refueling of a debris removal mission and a commercial satellite.
- **Canada** is developing robotic arm capabilities for NASA's planned Gateway space station in lunar orbit. The Canadarm3 aims to perform autonomous tasks on the station and has a planned delivery of 2029 to Gateway.
- **India** successfully docked two spacecraft together in orbit in January 2025 as a step toward satellite servicing and other missions.
- **Russia** plans to launch the first segment of a new space station in 2027, which will be assembled with five additional modules by 2033.
- **Australia** is partnering with India for its India Projects program, which gives grants to industry for space science. Missions supported by the grants include a demonstration of on-orbit transportation and debris mitigation, scheduled for launch in 2026.

Appendix V: GAO Contact and Staff Acknowledgments

GAO contact

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In addition to the contact named above, the following STAA staff made key contributions to this report:

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