Game Changer

ON-ORBIT SERVICING: INSPECTION, REPAIR, REFUEL, UPGRADE, AND ASSEMBLY OF SATELLITES IN SPACE

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Technological progress in space operations autonomy and robotics will disrupt the traditional paradigm of spacecraft design, acquisition, launch, operations, and maintenance. Within the next 5 to 10 years, routine spacecraft refueling could become a reality, and spacecraft low on propellant could avoid decommissioning and enjoy extended lifetimes. A new generation of cooperative spacecraft designed specifically for on-orbit servicing (OOS) could upgrade their own hardware every few years—a need that has been identified by the commercial, civil, and military satellite sectors. This would end the current paradigm of relying on satellites with decades-old hardware and technology, then having to launch replacements to modernize them.

The future impacts of OOS—from satellite acquisition to space architecture perspectives—are explored herein. While the market and growth trends for OOS could be temporarily dampened by the small, inexpensive, and disposable satellite designs currently being considered for low Earth orbit (LEO) constellations, many geosynchronous Earth orbit (GEO) satellite operators are finding an increasing need to extend satellite lifetimes. Longer-term, LEO constellations have also warranted an interest in OOS architecture and practices.

Technology	Market Readiness
On-Orbit Servicing  Image Credit: DARPA	**Demonstration Phase** • Routine use of OOS on ISS • Orbital Express' successful 2007 demonstration • NASA, DARPA, and the commercial sector are expected to demonstrate initial operational capability of robotic OOS within the next five years.
Strengths	**Weaknesses**
OOS provides capabilities to refuel, repair, upgrade, and enhance existing and future satellites. Servicers can also actively remove debris. Next-generation satellites and space architectures can become more flexible and cheaper to build and operate. OOS can enable the assembly of large structures such as telescopes and habitats in space.	Increased OOS activities may lead to operational failures that could damage client spacecraft and/or generate debris in high-value orbits such as GEO. Small spacecraft with short lifespans are cheaper to replace than service.

Introduction

Satellites are uniquely alone in their environment. They are launched with everything they need for their entire mission, from initial operational capability (IOC) to end of life. This has been the norm of civil, commercial, and military spacecraft design since Sputnik was launched on October 4, 1957. Over time, this led to fully redundant designs and very long mission life. With some exceptions, the ability to physically upgrade, refuel, or repair satellites once they are on orbit does not currently exist.

However, limited on-orbit servicing (OOS) activities have been performed since the early days of space endeavors.[1] Gemini and Apollo missions demonstrated rendezvous and proximity operations (RPO). Skylab and Solar Maximum Mission (SMM) demonstrated on-orbit repairs to fix critical components, with SMM taking advantage of a modular design using orbital replacement units (ORUs). Hubble Space Telescope (HST) was serviced five times, which included replacement of circuit boards. The International Space Station (ISS) was assembled on orbit and is continually replenished with propellant, supplies, and new modules to enhance its capabilities and provide new science opportunities. These activities were all performed by humans or with significant human-in-the-loop presence. However, the Defense Advanced Research Projects Agency's (DARPA's) Orbital Express (OE) demonstrated a full end-to-end robotic satellite servicing mission that included autonomous docking, fuel transfer, and ORU change-out—essentially removing humans from the equation.

While OOS activities have mostly been performed by government agencies—with NASA being the most prolific developer and user of the technology—the commercial space sector is beginning to move toward robotic servicing as an integral part of its space architectures.

The Outer Space Treaty of 1967 and the Space Liability Convention of 1972 are the current international laws governing OOS, though not explicitly. Domestically, the Federal Communications Commission (FCC) and National Oceanic and Atmospheric Administration (NOAA) have provided ad-hoc operating licenses needed for OOS activities.[2] Although this paper focuses on OOS market maturity and technology adoption, legislative and policy drivers will also impact market adoption rates of OOS and should be monitored closely, as various efforts are currently underway to standardize and regulate the market.[3]

What Is On-Orbit Servicing?

Widely agreed-upon OOS terminology does not currently exist, but it can play a crucial role in establishing a cross-industry-unified understanding of various aspects and activities of OOS. Fortunately, the Consortium for Execution of Rendezvous and Servicing Operations (CONFERS),[4] NASA, DOD, the American Institute of Aeronautics and Astronautics (AIAA), and others are working on this, and will likely establish a formal lexicon soon.

OOS refers to on-orbit activities conducted by a space vehicle that performs up-close inspection of, or results in intentional and beneficial changes to, another resident space object (RSO). These activities include non-contact support, orbit modification (relocation) and maintenance, refueling and commodities replenishment, upgrade, repair, assembly, and debris mitigation. A space vehicle possessing equipment specifically designed to perform servicing operations is called a *servicer*.

An RSO receiving OOS is called a *client*. A client can be cooperative or non-cooperative in nature. A *cooperative* client offers features designed to aid in acquisition, tracking, rendezvous, mating, and/or servicing activities, with information (position, velocity, health/status, etc.) transfer between the servicer and client occurring via two-way crosslinks or ground contacts. An example of a cooperative client is a commercial resupply vehicle designed to mate with the ISS. A *non-cooperative* client does not offer features designed to aid in acquisition, tracking, rendezvous, mating, and/or servicing activities, and there is no information transfer between the servicer and client. Examples of non-cooperative clients are legacy satellites, derelict rocket bodies, and pieces of orbital debris. The degree of cooperability lies on a spectrum, and usually a client is neither entirely cooperative nor non-cooperative.

On-Orbit Servicing Capabilities

OOS covers a wide range of capabilities:

Non-contact support refers to operations—near the client—by the servicer that enhance the client's capabilities or the servicer's knowledge of the client. Non-contact support is the only OOS function that does not require the servicer to mate with the client. Examples of non-contact support include inspecting the client to assist in anomaly resolution, and remotely enhancing the client with a new capability using a wireless connection.

Orbit modification and maintenance occurs when a servicer performs propulsion and attitude control functions for the client. Orbit modification, sometimes referred to as relocation or repositioning, is when the servicer spatially moves the client to a predetermined position and/or orbit. Orbit maintenance, or assistance, is when the servicer performs the stationkeeping and attitude-control functions for the client.

Refueling and commodities replenishment is a service that supplies commodities naturally depleted by the client over the course of its mission. Commodities include fluids such as propellants, pressurants, or coolants, but could also include other items such as dispensable objects.

Upgrade is the replacement or addition of components to a client to enhance the client's capability. Some examples are replacing a flight processor with a more capable one via ORUs, or installing a new payload into an existing structural, electrical, data, or thermal interface on the client. Upgrade can overlap with assembly, depending on the operation.

Repair is the replacement of components or correction of mechanical failures on a client to restore capability. Examples of this include replacing a failed battery with a new battery and assisting a solar array that failed to properly deploy.

Assembly[5] is an activity in which two or more objects intentionally combine to create a new space object or add an object to enhance an existing space vehicle. Examples include constructing a space station or large telescope, combining satlets to create a satellite, and adding a reflector dish to an existing satellite. Assembly can overlap with upgrade, depending on the operation.

Debris mitigation refers to a set of activities to locate, identify, and/or reposition RSOs, including but not limited to unresponsive space vehicles incapable of moving themselves, rocket bodies, or orbital debris. Debris mitigation will typically be performed in high-value-orbit regimes such as GEO or LEO.

Innovators and Market Leaders: On-Orbit Servicers

Robotic OOS is not a new concept. In fact, the enabling technologies have been steadily progressing over many decades. The tools, procedures, and systems required for robotic OOS are rapidly reaching maturity. Government and commercial entities are currently developing robotic systems that, in the next five years, will conduct OOS activities on operational systems to extend or enhance their mission capabilities. This section will discuss the development of the OOS market as well as current and planned OOS missions.

The Chicken-and-Egg Problem: Cooperative Satellites vs. Satellite Servicers

One of the primary barriers to the commercial servicing market has been the OOS business case "chicken-and-egg" problem. Satellite owners have been unwilling to pay for features to make servicing easier, because there have been no operational servicers. Moreover, operators may only require such a service for a small portion of their existing fleet. Yet, companies interested in offering OOS need an adequate, addressable market to justify the substantial capital investment required to develop servicers capable of performing operations on legacy satellites.

Overcoming this problem has been a challenge, but rapid progress is being made in developing a servicing market. Fortunately, some satellites have required OOS to perform their missions and have thus overcome the economics of developing servicing technologies. For example, HST and ISS both required OOS and so significant efforts and investment were made to service these missions. Investments from NASA, DARPA, and commercial entities are driving down the cost of developing robotic servicers. As the technical risks of robotic servicing are retired and the cost of building servicers is reduced, civil and commercial entities are beginning to incorporate OOS in future concepts.

NASA is developing future concepts and architectures—such as the Lunar *Gateway* and manned Mars missions—that will require significant use of OOS and is looking to the commercial sector to provide those services, much as they do today for the ISS. Commercial satellite operators recognize that their current fleets last longer than their design lives and find it increasingly hard to compete with terrestrial systems that enjoy rapid technology refresh cycles. They are concluding that OOS will be vital for maintaining their current businesses into the future. Companies looking to exploit cislunar (and beyond) development have business plans that are largely or entirely reliant upon a robust OOS infrastructure.

The servicing industry has reached a tipping point at which a commercially viable OOS capability is becoming a reality. Advancement of technology, demonstration missions that reduce risk, and the prospect of customers throughout industry are driving the development of an OOS commercial market.

Recent, Ongoing, and Upcoming OOS Missions and Services

End-to-end robotic OOS was first demonstrated by OE in 2007. Since OE's successful mission more than a decade ago, a significant amount of work has been done to advance the technologies and develop the business cases to establish a viable OOS market. Today, many companies and government organizations are still exploring OOS. With the success of several demonstration missions over the past few years, commercial initial operational capability (IOC) is rapidly approaching. Table 1 highlights many concepts being explored and recent demonstration successes throughout the space industry. This table is not an exhaustive list of all concepts but does highlight many of the technology and market leaders throughout the space industry.

Game Changer Lifecycle: Market and Technology Phases and Triggers

Robotic OOS advancements have reached the tipping point of technical feasibility, acceptable mission risk levels, and business case viability. Civil and commercial entities, inside and outside the U.S., are beginning to field prototypes and are nearing IOC for robotic servicers and on-orbit commercial services. These near-term activities are now influencing future spacecraft system design and space segment architectures. In fact, plans for future space systems are beginning to look drastically different from today's systems and architectures. Figure 1 (see page 7) lays out the expected path of OOS maturation and adoption. A description of the chart is as follows:

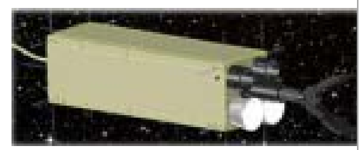
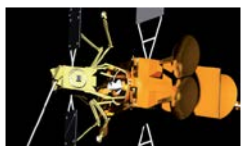
- The far-left column shows key technology areas that have been undergoing research and development for decades. Many of these technologies have direct terrestrial applications, such as robotic arms for manufacturing and medical use, having received ample funding for their development. Other technologies are specific to space environment applications, such as fluid transfer systems for operation in microgravity, and are more reliant on entities such as NASA for technology maturation. Current technologies are all at or above Technology Readiness Level 6 and are expected to fly on operational servicers within the next five years.

- The second column shows past and present OOS activities. While many previous servicing applications have gone unmentioned in this graphic (especially international activities), it is key to note the extensive history of OOS. Also listed in this column are the planned NASA Restore-L mission, DARPA's Robotic Servicing of Geosynchronous Satellites (RSGS) mission, and the introductory commercial servicers, to include the Mission Extension Vehicle (MEV) and InsureSat, all of which contribute to OOS capabilities.

- The third and fourth columns show expected future paths of market growth as OOS becomes pervasive and mature. Commercial entities will be both the providers *and* benefactors of servicing for a wide range of capabilities that will emerge and build from initial market entrants. It is expected that manufacturers of larger spacecraft systems will transition to modular design practices to accommodate and enable OOS for their customers. NASA is looking to continue development of large structures in space, such as the Lunar Gateway,[6] that will require large module assembly in lunar orbit—as well as future large flagship telescopes, such as the Large Ultraviolet Optical Infrared (LUVOIR) telescope,[7] that are being designed for OOS from the beginning, with regular servicing and upgrading baselined into the operations.

Table 1: On-Orbit Servicing Market Leaders

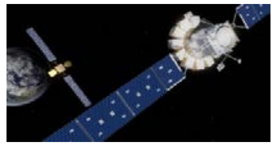
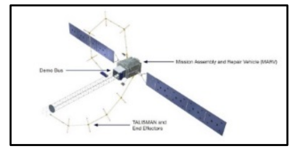
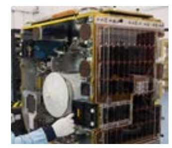
Commercial

Airbus (Toulouse, France): O. CUBED[8]  Image source: Airbus Airbus is exploring LEO and GEO inspection, life extension, orbit modification, upgrade, and debris removal with its (on-orbit operations) O. CUBED services and Space Tug concepts.	***Altius Space Machines (Broomfield, Colorado): Bulldog[9]***  Image source: Altius Altius' Bulldog conceptual spacecraft will provide a disposal service to the proposed Mega LEO constellations.	***Astroscale (Tokyo, Japan): ELSA-d[10]***  Image source: Astroscale Astroscale's Space Sweeper satellites will help clean up space by performing active debris removal end-of-life disposal services.	***Busek (Natick, Massachusetts): SOUL[11]***  Image source: Busek Busek's Satellite on an Umbilical Line (SOUL) concept is a small spacecraft tethered to a host to perform inspection, spacecraft repair, debris removal, and other on-orbit services.
Chandah Space Technologies (Houston, Texas): InsureSat[12] Image source: CST Chandah Space Technologies (CST) has received a license to operate its remote sensing inspection satellite, InsureSat, in GEO.	***Effective Space (London, UK) & IAI (Lod, Israel): Space Drone[13]***  Image source: Effective Space Effective Space and Israel Aerospace Industries (IAI) are teaming up on their Space Drone conceptual spacecraft, set for launch in 2020,[16] to perform life-extension services.[17]	***iBOSS (Aachen, Germany): iBOSS[14]***  Image source: iBOSS GmbH Intelligent Building Blocks for On-Orbit Satellite Servicing and Assembly (iBOSS) is using standardized interfaces and modularity to design and manufacture reconfigurable spacecraft for on orbit servicing and assembly.	***Maxar (Westminster, Colorado): Dragonfly[15]***  Image source: SSL Maxar is developing an on-orbit assembly capability, Dragonfly, to augment and assemble satellites and other space infrastructure on orbit.

Made In Space, Inc. (Mountain View, California)

Additive Manufacturing Facility[18]  Image source: Made In Space MIS' AMF, launched in March 2016, is currently providing the only 3D-printed, hardware-manufacturing service in space, onboard the ISS.	***Archinaut[19]***  Image source: Made In Space MIS' Archinaut concept is designed to manufacture and assemble large-scale structures on orbit.	***Fiber Optics Manufacturing[20]***  Image source: Made In Space MIS' fiber optic cable facility, launched in September 2017, is manufacturing ZBLAN in microgravity, with unique properties for terrestrial use.

Table 1: On-Orbit Servicing Market Leaders

Northrop Grumman Innovation Systems (Dulles, Virginia)		
Mission Extension Vehicle[21]  Image source: Northrop Grumman Two Mission Extension Vehicles (MEVs), set for launch in 2019[22] and 2020,[23] will execute contracts with Intelsat for life-extension services.[24]	***Mission Robotic Vehicle***[25]  Image source: Northrop Grumman The Mission Robotic Vehicle (MRV) is a next-gen MEV and will also be able to provide inspection, upgrade, and repair services.	***CIRAS***[26]  Image source: Northrop Grumman The Commercial Infrastructure for Robotic Assembly and Services (CIRAS) concept will build on the MEV and MRV to enable assembly and servicing of large-scale structures.
NASA: ***ISS Commercial Resupply***[27]  Image source: NASA NASA's ISS Commercial Resupply Services program has enabled companies like SpaceX and Northrop Grumman Innovation Systems to develop and generate revenue from rendezvous and proximity operations systems for logistics services.	***Public-Private Partnership (DARPA, USA):*** ***RSGS***[28]  Image source: DARPA DARPA's Robotic Servicing of Geosynchronous Satellites (RSGS), set for launch in 2021, will perform inspection, repair, relocation, and upgrade. A commercial partner is currently TBD.	***RemoveDEBRIS Consortium*:*** ***RemoveDEBRIS***[29]  Image source: SSTL The RemoveDEBRIS mission, launched in June 2018, demonstrated debris-removal technologies as a precursor to the ESA's e.Deorbit initiative. *The RemoveDEBRIS Consortium includes Airbus, Surrey Satellite Technology, Ltd. (SSTL), ArianeGroup, Swiss Center for Electronics and Microtechnology (CSEM), Inria, Innovative Solutions in Space (ISIS), Surrey Space Centre, and Stellenbosch University

Civil and Government			
Harbin Institute of Technology (China): ***Aolong-1***[30] No Image Available Aolong-1, launched in June 2016, demonstrated technology and procedures for small debris removal.	***National University of Defense Technology (China):*** ***Tianyuan-1***[31] No Image Available Tianyuan-1, launched in June 2016, demonstrated technology and procedures for on-orbit refueling.	***DARPA (USA):*** ***Orbital Express***[32]  Image source: DARPA Orbital Express, launched in March 2007, demonstrated autonomous rendezvous, docking, refuel, and upgrade.	***ESA (EU):*** ***e.Deorbit***[33]  Image source: © ESA - D. Ducros The e.Deorbit initiative aims to robotically deorbit ESA objects to demonstrate OOS technologies.

NASA (USA)			
ISS[34]  Image source: NASA The ISS, a football field-sized station assembled on orbit, is continually resupplied with fuel and upgraded with new technology and payloads.	***Lunar Gateway***[35]  Image source: NASA The Lunar Gateway, the next space station, will be assembled in lunar orbit starting in 2022 with the launch of the power and propulsion element.	***Restore-L***[36]  Image source: NASA Restore-L, set for launch in late 2022, will refuel and reposition Landsat 7—a satellite launched in 1999.	***RRM***[37,38] ***& Raven***[39]  Image source: NASA The Robotic and Refueling Mission (RRM) and Raven missions, currently hosted on the ISS, are demonstrating on-orbit refueling and robotic vision technology.

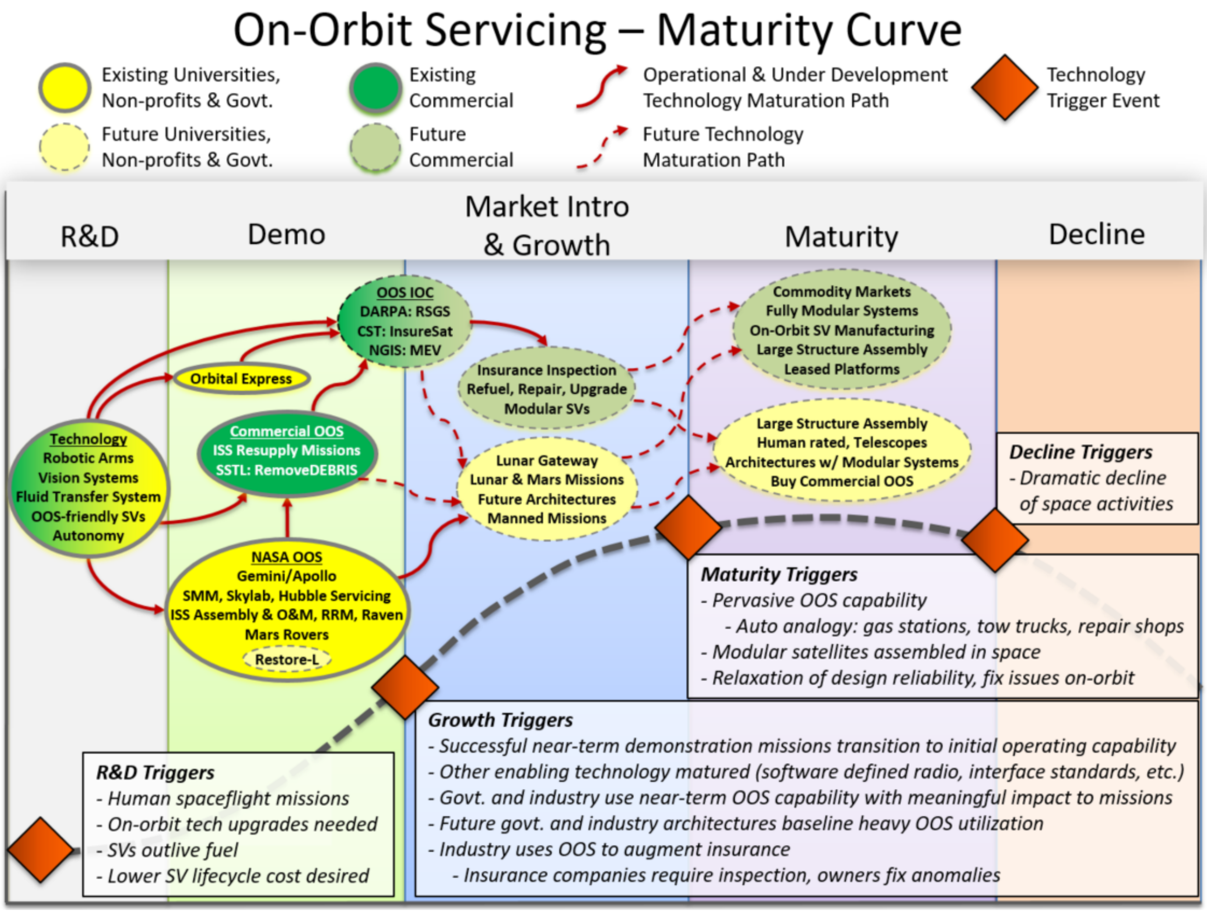


Figure 1. The anticipated maturity curve and technology maturation path of OOS.

- This figure also shows OOS trigger events that may spur movement along the maturity curve.

  - Research and development triggers highlight events that may initiate a directed effort among the community to mature technology and market adoption. NASA's efforts to explore space have been the driving factor for OOS development to date. Their human spaceflight lunar missions and space stations have required significant amounts of RPO and servicing activities on a consistent basis to be successful. Recent interest by commercial companies has resulted in additional development efforts to extend existing satellite lifetimes and provide more flexibility to satellite owners and operators in designing their satellite architectures and developing their business plans.

  - Growth triggers include completion of demonstration activities, which matures technology components. Commercial resupply missions to the ISS are also included in this category due to the consistent need to perform RPO.[27] In the next few years, many civil and commercial missions will demonstrate robotic OOS and begin to offer commercial services to enhance existing satellites. If these missions are successful, the space industry will likely see a rapid growth of OOS capabilities resulting in reduced operating cost—which includes servicer use in satellite insurance contracts to mitigate or repair failures in lieu of replacing spacecraft.

  - Maturity triggers will signal when the OOS technology has moved into a mature phase within the space market. This is highlighted by a pervasive OOS capability, similar to how we operate and maintain cars or airplanes today. Satellites will no longer be launched with a lifetime of fuel; they will be refueled throughout their lifetimes. Satellites will be designed modularly so that components or even payloads may be added post-launch. Reliability requirements may be relaxed, resulting in a lower development and assembly, integration, and test cost due to the reliance of on-orbit repairability.

- Finally, decline triggers will signal when the OOS capabilities may start becoming obsolete. Even small, cheap satellites can benefit from some degree of OOS, so it is unlikely that new technologies or architectures will result in a greatly decreased use of OOS, though the types of servicing being performed will likely evolve over time. Only a dramatic decline of space activities would negate the need for OOS.

While the OOS technology has matured rapidly and is at a point where robotic servicing of satellites is technically feasible, many market issues persist. The near-term development of the OOS market relies on the success of near-term programs as well as the future of space architectures.

The announcement of Maxar's departure from DARPA's RSGS program[40] is being viewed by some as a sign that the OOS market may *not* be ready for commercial investment. The slowdown in the commercial communications GEO market, a failure of the WorldView-4 satellite[41], and limited corporate resources are the more likely causes of Maxar's decision to depart from the program, rather than a technical or business case impasse.[42] DARPA is currently considering how to move forward with the program and has released an industry survey for new partnership opportunities.[43]

If near-term OOS demonstrators suffer failures, either technical or programmatic, the market may shy away from OOS, at least until more successful demonstrations occur. This would delay the adoption of OOS and require greater investments. However, OOS is widely viewed as the most viable path forward for continuing to expand space activities beyond their present limitations. Near-term failures will only be a temporary setback for progressing toward a mature OOS market.

It is also possible that future space architectures may heavily emphasize small, cheap, "disposable" spacecraft, such as those currently being explored by the large LEO constellations proposed by OneWeb, SpaceX, and many others.[44] Even DARPA is weighing whether a large LEO constellation may make sense for DOD applications.[45] In these architectures, the role for OOS could be diminished, but commercial companies are still finding that there may be a viable OOS market with large LEO constellations. For instance, Altius Space Machines' BullDog™ concept is a deorbiter for failed satellites in LEO.[9]

The OOS maturity curve presented here is a projection of current market trends into future architectures. For now, the OOS capabilities appear to be on the path laid out.

Market Drivers: On-Orbit Servicing Impacts on the Cost of Space Activities, Spacecraft Design, and Space Architecture

While OOS is still in its infancy, the potential market implications, even in the near term, are enormous. Today, no commercial servicers exist, and only government entities have performed OOS. That trend is changing, however. Chandah Space Technologies, SpaceLogistics LLC (a wholly owned subsidiary of Northrop Grumman), and numerous other companies are working to bring commercial services to the space market. Over time, the capabilities of the OOS market will expand, growing from the near-term MEV, Restore-L, and RSGS-like capabilities, into complex space architectures that rely on refueling, upgrading, assembly, and manufacturing.

These market capabilities are especially noteworthy due to the recently announced failure of Intelsat-29e.[46] Intelsat suffered a fuel leak followed by a communication system failure, resulting in the loss of a satellite 3 years into its 15-year design life. An on-orbit servicing infrastructure could have played an important role in the aftermath of these failures and potentially could have helped to salvage the space vehicle, which will ultimately cost hundreds of millions to replace. Inspection could have helped diagnose failure mechanisms and provided critical data inputs to failure review findings and insurance payouts. Orbit modification could have (and may in the future) moved Intelsat-29e out of the GEO belt, removing a large piece of debris from a high-value orbit. Repair could have potentially fixed the propellant leak and/or communication system failure, restoring some of the satellite's capability, though it is unlikely this capability would be ready in time to save this satellite.

Mission Extension Services: Inspection, Orbit Maintenance and Modification, and Refueling

Satellite services in the next 5 to 10 years will likely be limited to inspection, orbit modification and maintenance, and refueling of legacy non-cooperative satellites. RSGS will contain some additional capability to perform basic repair or attachable upgrade functions.[47] The next generation of MEVs[48] and the European Space Agency's Clean Space Initiative[49] missions are also envisioned to have a similar capability. However, the market impact of these capabilities is more limited than that of extending spacecraft lifetime via refueling or taking over propulsion and attitude-control functions.

Satellites living beyond their design life has become the norm, and operators are reluctant to decommission satellites simply because they are running low on fuel. Some estimates show that more than 50 percent of GEO satellites will experience operational impacts due to fuel depletion.[50] Government and commercial operators can find value in almost any space asset if they can still communicate with it. At the Space Tech Conference, May 2018, both SES and IntelSat commented on their ability to monetize value from aging spacecraft, and how both companies were looking to OOS life-extension capabilities as a part of their business models going forward.[51]

With the introduction of mission-extension services, satellite owners can delay capital expenditures, maintain assets in valuable GEO slots, and prolong the life of productive and profitable space vehicles. Also, if satellite life is not limited by onboard consumables, a secondary market in older-but-functional spacecraft will likely emerge, similar to the used car market. Companies or governments unable or unwilling to purchase new satellites instead might buy used ones.

The satellite insurance market will also see significant impacts due to the introduction of servicing capabilities.[52] Insurance companies can use servicers for inspection to determine whether claims worth hundreds of millions of dollars must be paid. They may also use servicers to fix deployment anomalies or refuel satellites to replenish propellant expended due to launch insertion anomalies, thereby restoring capability at less cost than paying a full claim. Over time, satellite owners might self-insure their constellations and use insurance to cover only the earliest and riskiest parts of the mission, relying on servicers to cover failures thereafter.

Future Spacecraft Designs: Modularity, Repairability, and Upgradability

As the success of OOS materializes, satellite designs will begin to incorporate cooperative servicing features such as standard quick-disconnect refueling valves; machine vision-friendly fiducials; grapple fixtures; and common structural, power, data, and fluid interfaces. Spacecraft currently being acquired are already studying serviceability features, and by the end of the 2020s, it is likely that all large satellite acquisitions will require cooperative designs for servicing.

While designing for full serviceability means a change in current satellite design practices, it has been shown that modular designs can be cost-neutral compared to traditional highly integrated designs when considering more than a single satellite purchase.[53] The increased cost of modular system design is largely offset during the assembly, test, and integration phases of the acquisition cycle. Modular designs tend to increase satellite dry mass compared to highly optimized designs, but those weight penalties can be recovered using the benefits of OOS.

Modular satellites designed for upgradability and refueling have distinct advantages. They can be launched with less fuel than needed for the entire mission, saving hundreds of kilograms in launch weight. This could also increase the launch vehicle throw-weight margins. The ability to add or replace components on orbit (via standard interfaces) means that satellites can be designed with less redundancy. Furthermore, satellites can launch without a non-critical component or payload if their production is late, thereby maintaining launch schedules—OOS can install the missing element later. This enhanced flexibility may also significantly alter the paradigm of spacecraft mission assurance, reducing the need to perform lengthy and costly test campaigns by relying on the ability to repair and replace failed components on orbit.

As modularity and standardized interfaces become more pervasive throughout the satellite manufacturing industry, costs will inevitably decrease. Standardized plug-and-play capabilities have benefited many industries, such as home computers. Desktop computers are highly modular systems with hardware and software standard interfaces.

Individual computer components can be purchased and assembled by relatively inexperienced people. Failed or outdated components can be easily swapped with new components without having to buy an entirely new computer. Standard interfaces enable a wide variety of options and reduce both consumer costs and entry barriers within the industry. The same trend is likely to occur with spacecraft as modular designs become more common. The definition of industry-wide standard interface specifications, similar to a Universal Serial Bus (USB), would likely reduce the barriers of entry, increase competition, and decrease satellite acquisition costs. Companies such as iBOSS, along with many others throughout the space industry, are looking to define standardized interfaces and develop modular spacecraft.

At the Space Tech Conference in May 2018, both SES and IntelSat commented on their desire to purchase satellites with 30-year lifetimes, but with payloads that could be upgraded every 5 years.[51] This would be entirely reliant on satellite servicing, as an extremely long-lived satellite bus would require routine maintenance and refueling, similar to terrestrial systems. Regular payload reconfiguration or upgrade would absolutely require a servicer unless the upgrades could be performed entirely through software updates, which is unlikely to be sufficient over a 30-year time span.

A satellite that can replace or upgrade its payload every few years has the potential to significantly reduce the cost of space activities and even open new markets. Long-life platforms that provide power, propulsion, pointing, thermal control, and other satellite bus functions could host payloads for a variety of customers, which would change over time, creating a revenue stream for the platform owner and reducing the cost of space operations for the payload operators. These types of platforms may lead to a new business model for space activities such as leasing vs. buying satellites, similar to homes and offices. Leasing time on a space platform would be significantly cheaper and have far less risk than building and launching a highly integrated spacecraft for one dedicated mission.

A comprehensive OOS capability is likely to become an economic necessity as market forces push for reduced cost and risk of space activities. As servicing becomes pervasive and the cost of space access is reduced, additional capabilities will become all the more feasible.

Next Generation Space: On-Orbit Manufacture and Assembly of Spacecraft

As servicing activities become more complex, and space architectures begin to incorporate serviceability, the demand for OOS will dramatically increase as the cost of performing servicing decreases. On-orbit manufacturing and assembly will likely result from this sort of robust space economy.[5] Satellites manufactured and assembled in space will have significant technical advantages over satellites manufactured and assembled on the ground and then launched into space.

Assembly of structures in space has been demonstrated by the ISS, a football field-sized structure assembled by the international space community over two decades. NASA is also exploring assembly for its next generation of large telescopes; missions larger than the James Webb Space Telescope (JWST) exceed launch vehicle fairing volume restrictions. Assembly, however, is not just limited to large structures. NASA and industry are working on concepts that include partial assembly of satellites on orbit, which entails replacing deployable structures with assembled structures to maximize packaging efficiencies,[54] as well as assembly of entire "traditional" satellites from modular components.[55]

On-orbit assembly offers many benefits—the most obvious being freedom from the tyranny of fairing constraints.[5] Spacecraft must fit within the volume restrictions of the launch vehicle fairing,[56] as well as within the mass-to-orbit capability of the system. Spacecraft launched in pieces and assembled on orbit would be much less limited by their size or mass, much as the ISS could never have been launched in one piece. Satellites with large deployable structures, such as the JWST, currently have significant design restrictions due to the launch vehicle fairing volume limitations, but future systems could launch extremely large satellite apertures separately or in pieces for on-orbit assembly.

Small satellites would also gain significantly from on-orbit assembly. Currently, one of the biggest drivers in satellite design is survival of the launch environment. Being launched on a rocket involves significant accelerations, vibrations, and mechanical shocks. An integrated system must be built to survive these environmental factors, but these environments are only present for a few minutes of a satellite's multi-year lifetime. If a satellite could be broken down into modules, packaged individually, and assembled on orbit, the structural design could be greatly simplified.

In addition to assembly, the space industry is looking toward on-orbit manufacturing as having enormous potential for utility much closer to home. For example, companies like Made In Space, Inc. are exploring the manufacturing of materials in space for terrestrial applications.[57] Many companies are looking at mining ice water from various celestial bodies and converting it into propellant (LH2/LOX) to be sold as a commodity. Eventually, 3D-printing techniques could become sophisticated enough to print electronics or even an entire spacecraft. A satellite manufactured on orbit would look significantly different from one manufactured on the ground; the former could take advantage of materials that cannot be exposed to air, avoid the structural limitations of being built in a standard gravity environment, and be configured in virtually limitless sizes and shapes. Even satellites built terrestrially in a modular fashion and assembled on orbit would look significantly different from those manufactured and built entirely on orbit. Large truss structures and apertures that can be printed on orbit are currently being explored for demonstrations.[58]

Conclusion

OOS is at a tipping point, and while NASA will continue to need servicing for the ISS, Lunar Gateway, and other concepts, the economics of space operations are driving the commercial implementation of OOS capabilities. In response to this market demand, OOS will continue to mature as multiple commercial satellite companies plan to offer services in the next few years. As a result, civil and commercial satellite owners and operators are beginning to explore how to leverage these capabilities to enhance their existing constellations, and how to optimize and prepare their next generation of spacecraft for the coming paradigm shift. Although more sophisticated and longer lasting, satellites today are the same lonely outposts that have existed since the Sputnik era. In contrast, satellites launched a decade from now will have servicing companions and be designed for this communal environment.

Acronyms

AIAA	American Institute of Aeronautics and Astronautics
CIRAS	Commercial Infrastructure for Robotic Assembly and Services
CONFERS	Consortium for Execution of Rendezvous and Servicing Operations
CST	Chandah Space Technologies
DARPA	Defense Advanced Research Projects Agency
DOD	Department of Defense
ELSA-d	End-of-Life-Service by Astroscale demonstration
ESA	European Space Agency
EU	European Union
FCC	Federal Communications Commission
GEO	geosynchronous Earth orbit
HST	Hubble Space Telescope
IAI	Israel Aerospace Industries
iBOSS	Intelligent Building Blocks for On-Orbit Satellite Servicing and Assembly
IOC	initial operational capability
ISIS	Innovative Solutions in Space
ISS	International Space Station
JWST	James Webb Space Telescope
LEO	low Earth orbit
LH2	liquid hydrogen
LOX	liquid oxygen
LUVOIR	Large Ultraviolet Optical Infrared
MEV	Mission Extension Vehicle
MIS	Made In Space
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration

O. CUBED	on-orbit operations
OE	Orbital Express
OOS	on-orbit servicing
ORU	orbital replacement unit
RPO	rendezvous and proximity operations
RRM	Robotic Refueling Mission
RSGS	Robotic Servicing of Geosynchronous Satellites
RSO	resident space object
SCEM	Swiss Center for Electronics and Microtechnology
SMC/AD	Advanced Systems and Development Directorate
SMM	Solar Maximum Mission
SOUL	Satellite on an Umbilical Line
SSL	Space Systems Loral
SSTL	Surrey Satellite Technology, Ltd.

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References

[1] "On-Orbit Satellite Servicing Study Project Report," NASA GSFC, October 2010, https://sspd.gsfc.nasa.gov/images/nasa_satellite%20servicing_project_report_0511.pdf.

[2] C. Henry, "FCC begins approval of Orbital ATK satellite-servicing mission for Intelsat-901," *SpaceNews*, December 2017, https://spacenews.com/fcc-begins-approval-of-orbital-atk-satellite-servicing-mission-for-intelsat-901/.

[3] R. Reesman, A. Rogers, "Getting in Your Space: Learning from Past Rendezvous and Proximity Operations," Center for Space Policy and Strategy, May 2018, https://aerospace.org/paper/your-space-rendezvous-and-proximity-operations-lessons.

[4] CONFERS, August 2018, https://www.satelliteconfers.org/.

[5] D. Piskorz, K. Jones, "On-Orbit Assembly of Space Assets: A Path to Affordable and Adaptable Space Infrastructure," Center for Space Policy and Strategy, February 2018, https://aerospace.org/paper/orbit-assembly-space-assets.

[6] J. Crusan, "Future Human Exploration Planning: Lunar Orbital Platform-Gateway and Science Workshop Findings," March 2018, https://www.nasa.gov/sites/default/files/atoms/files/20180327-crusan-nac-heoc-v8.pdf.

[7] "Large UV/Optical/IR Surveyor," NASA, August 2018, https://asd.gsfc.nasa.gov/luvoir/.

[8] "O.CUBED Services," Airbus, August 2018, https://www.airbus.com/space/on-orbit-services.html.

[9] Altius Space Machines, "Open Source Analysis of Iridium Failures and the Implications for Big LEO Constellations," Spacecraft Anomalies and Failures (SCAF) 2017 Workshop, December 2017, http://www.altius-space.com/wp-content/uploads/2018/02/AltiusSCAFPresentation-ImplicationsOfIridiumOnBigLEO_12Dec2017.pdf.

[10] Astroscale, "ELSA-d" https://astroscale.com/missions/elsa-d/.

[11] V. Hruby, C. DeLuccia, and D. Williams, "Tethered Robot for Spacecraft Self Inspection and Servicing," 2018 AIAA SPACE Forum, September 2018, https://arc.aiaa.org/doi/pdf/10.2514/6.2018-5342.

[12] "Chandah Space Technologies Private Remote Sensing License," NOAA, August 2017, https://www.nesdis.noaa.gov/CRSRA/files/CST_Public_Summary_Aug_11_2017.pdf.

[13] J. Foust, "Effective Space announces partnership with IAI for satellite servicing development," *SpaceNews*, September 2018, https://spacenews.com/effective-space-announces-partnership-with-iai-for-satellite-servicing-development/.

[14] "iBOSS," iBOSS, August 2018, https://www.iboss.space/.

[15] "NASA's Dragonfly Project Demonstrates Robotic Satellite Assembly Critical to Future Space Infrastructure Development," NASA, September 2017, https://www.nasa.gov/mission_pages/tdm/irma/nasas-dragonfly-project-demonstrates-robotic-satellite-assembly-critical-to-future-space.html.

[16] C. Henry, "Effecitve Space reserves ILS Proton rideshare for two satellite servicers," *SpaceNews*, March 2018, https://spacenews.com/effective-space-reserves-ils-proton-rideshare-for-two-satellite-servicers/.

[17] O. Gadel, "IAI to build Space Drones for Maintenance Missions," Tech Time, September 2018, https://techtime.news/2018/09/16/iai-4/.

[18] "Additive Manufacturing Facility," Made In Space, Inc., August 2018, http://madeinspace.us/projects/amf/.

[19] "Archinaut," Made In Space, Inc., August 2018, http://madeinspace.us/archinaut/.

[20] "Fiber Optics," Made In Space, Inc., August 2018, http://madeinspace.us/mis-fiber/.

[21] "Mission Extension Vehicle," Northrop Grumman, August 2018, (http://www.northropgrumman.com/Capabilities/SpaceLogistics/Documents/MEV_Factsheet.pdf.

[22] C. Bergin, "ILS announce two future launches, including the test of orbital ATK's MEV-1," *NASASpaceFlight.com*, October 2016, https://www.nasaspaceflight.com/2016/10/ils-future-missions-launch-orbital-atks-mev-1/#more-47338.

[23] "Intelsat signs contract with Arianespace for two launches," *Arianespace*, January 2018, http://www.arianespace.com/press-release/intelsat-signs-contract-with-arianespace-for-two-launches/.

[24] S. Erwin and C. Henry, "Orbital ATK lands second Intelsat satellite servicing deal," *SpaceNews*, January 2018, http://spacenews.com/orbital-atk-lands-second-intelsat-satellite-servicing-deal/.

[25] "Orbital ATK introduces Next Generation of In-Orbit Satellite Servicing Technology," Northrop Grumman, March 2018, https://news.northropgrumman.com/news/features/orbital-atk-introduces-next-generation-of-in-orbit-satellite-servicing-technology.

[26] K. Pittman, "Manufacturing in Space with Robots and 3D Printing," engineering.com, July 2017, https://www.engineering.com/AdvancedManufacturing/ArticleID/15324/Manufacturing-in-Space-with-Robots-and-3D-Printing.aspx.

[27] "Commercial Resupply Servicers Overview," NASA, August 2018, https://www.nasa.gov/mission_pages/station/structure/launch/overview.html.

[28] J. Parrish, "Robotic Servicing of Geosynchronous Satellites," DARPA, August 2018, https://www.darpa.mil/program/robotic-servicing-of-geosynchronous-satellites.

[29] "RemoveDEBRIS deployed into Low Earth Orbit from the ISS," Surrey, June 2018, https://www.sstl.co.uk/media-hub/latest-news/2018/removedebris-deployed-into-low-earth-orbit-from-th.

[30] "China's new Orbital Debris Clean-Up Satellite raises Space Militarization Concerns," SpaceFlight101, June 2016, http://spaceflight101.com/long-march-7-maiden-launch/aolong-1-asat-concerns/.

[31] J. Lin and P. Singer, "China's largest space launch vehicle, the Long March 7 flies, with a Technological Triple Whammy," Popular Science, July 2016,

https://www.popsci.com/chinas-largest-space-launch-vehicle-long-march-7-flies-with-technological-triple-whammy.
[32] R. Friend, "Orbital Express program summary and mission overview," Proc. SPIE 6958, Sensors and Systems for Space Applications II, 695803, April 15, 2008, https://www.spiedigitallibrary.org/conference-proceedings-of-spie/6958/695803/Orbital-Express-program-summary-and-mission-overview/10.1117/12.783792.full?SSO=1.
[33] ESA, "Removing Debris to Demonstrate Commercial In-Orbit Servicing," The Clean Space Blog, August 2018, http://blogs.esa.int/cleanspace/2018/09/06/removing-a-debris-to-demonstrate-commercial-in-orbit-servicing/.
[34] "International Space Station," NASA, August 2018, https://www.nasa.gov/mission_pages/station/main/index.html.
[35] M. Wall, "NASA Plans to Build a Moon-Orbiting Space Station: Here's What You Should Know," SPACE.com, September 2018, https://www.space.com/41763-nasa-lunar-orbiting-platform-gateway-basics.html.
[36] "Restore-L Robotic Servicing Mission," NASA, August 2018, https://sspd.gsfc.nasa.gov/restore-l.html.
[37] "Robotic Refueling Mission," NASA SSPD, August 2018, https://sspd.gsfc.nasa.gov/robotic_refueling_mission.html.
[38] "Robotic Refueling Mission 3," NASA SSPD, August 2018, https://sspd.gsfc.nasa.gov/RRM3.html.
[39] "Raven," NASA SSPD, August 2018, https://sspd.gsfc.nasa.gov/Raven.html.
[40] "Maxar Technologies' SSL Terminates its Participation in DARPA's Robotic Servicing of Geosynchronous Satellites Program," Maxar Technologies, January 2019, http://investor.maxar.com/investor-news/press-release-details/2019/Maxar-Technologies-SSL-Terminates-its-Participation-in-DARPAs-Robotic-Servicing-of-Geosynchronous-Satellites-Program/default.aspx.
[41] "Maxar Technologies Reports Failure of its WorldView-4 Imaging Satellite," Maxar Technologies, January 2019, http://investor.maxar.com/investor-news/press-release-details/2019/Maxar-Technologies-Reports-Failure-of-its-WorldView-4-Imaging-Satellite/default.aspx.
[42] S. Erwin, "Maxar's exit from DARPA satellite servicing program a cautionary tale," *SpaceNews*, January 2019, https://spacenews.com/maxars-exit-from-darpa-satellite-servicing-program-a-cautionary-tale/.
[43] J. Keller, "DARPA considers re-launching project to develop a space robot to repair and upgrade orbiting satellites," Military & Aerospace, February 2019, https://www.militaryaerospace.com/articles/2019/02/space-robot-repair-and-upgrade-satellites.html.
[44] C. Henry, "LEO and MEO broadband constellations mega source of consternation," *SpaceNews*, March 2018, https://spacenews.com/divining-what-the-stars-hold-in-store-for-broadband-megaconstellations/.
[45] P. Thomas, "Blackjack," DARPA, February 2019, https://www.darpa.mil/program/blackjack.
[46] C. Henry, "Intelsat-29e declared a total loss," *SpaceNews*, April 2019, https://spacenews.com/intelsat-29e-declared-a-total-loss/.
[47] B. Sullivan, J. Parrish, and G. Roesler, "Upgrading In-service Spacecraft with On-orbit Attachable Capabilities," 2018 AIAA SPACE Forum, September 2018.
[48] J. Foust, "Orbital ATK unveils new version of satellite servicing vehicle," *SpaceNews*, March 2018, https://spacenews.com/orbital-atk-unveils-new-version-of-satellite-servicing-vehicle/.
[49] T. Pultarova, "European Space Junk Cleanup Concept Gets New Mission: Refuel and Repair," SPACE.com, January 2019, https://www.space.com/43157-e-deorbit-new-refuel-repair-mission.html.
[50] R. L. Hibbard, "Satellite On-Orbit Refueling: A Cost Effectiveness Analysis" Naval Postgraduate School, September 1996, https://core.ac.uk/download/pdf/36724990.pdf.
[51] D. Werner, "How long should a satellite last: five years, ten years, 15, 30?," *SpaceNews*, May 2018, https://spacenews.com/how-long-should-a-satellite-last/.
[52] R. Reesman, "Assurance Through Insurance and On-Orbit Servicing," Center for Space Policy and Strategy, February 2018, https://aerospace.org/paper/assurance-through-insurance-and-orbit-servicing.
[53] D. Rossetti, B. Keer, J. Paneck, B. Reed, F. Cepollina, and R. Ritter, "Spacecraft Modularity for Serviceable Spacecraft," 2015 AIAA SPACE Forum, September 2015.
[54] "NASA's Dragonfly Project Demonstrates Robotic Satellite Assembly Critical to Future Space Infrastructure Development," NASA, September 2017, https://www.nasa.gov/mission_pages/tdm/irma/nasas-dragonfly-project-demonstrates-robotic-satellite-assembly-critical-to-future-space.html.
[55] D. Werner, "Satlets: crazy idea or ingenious concept? This week's test on ISS will offer clues," *SpaceNews*, October 2017, https://spacenews.com/satlets-crazy-idea-or-ingenious-concept-this-weeks-test-on-iss-will-offer-clues/.
[56] C. O'Quinn, D. Piskorz, "Setting the Standard: Launch Units for the Smallsat Era," Center for Space Policy and Strategy, May 2018, https://aerospace.org/paper/setting-standard-launch-units-smallsat-era.
[57] "Fiber Optics: Best in Class Fluoride-Based Fiber for Medical, Telecom, and Research," Made In Space, Inc., August 2018, http://madeinspace.us/mis-fiber/.
[58] K. Pittman, "Manufacturing in Space with Robots and 3D Printing," engineering.com, July 2017, https://www.engineering.com/AdvancedManufacturing/ArticleID/15324/Manufacturing-in-Space-with-Robots-and-3D-Printing.aspx.