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Executive Summary

In the history of spaceflight, almost all spacecraft have been manufactured and assembled on the ground, then integrated into a launch vehicle for delivery into orbit. This approach imposes significant limitations on the size, volume, and design of payloads that can be accommodated within the fairing of a single launch vehicle. In particular, fairing diameter limitations restrict the size and number of instruments that can be fielded in orbit for science and national security missions. In turn, these constraints place definite limits on the information that can be obtained from spaceborne payloads. Design of spacecraft built on the ground requires all the components of each spacecraft to be hardened (*ruggedized*) to withstand the harsh launch environment, which includes severe vibrations, acoustics, acceleration loads, and thermal loads. The hardening processes impose penalties in terms of mass and size that ultimately limit payload capabilities and increase launch costs. These penalties are further compounded by the need for inclusion of redundant backup systems to provide contingency against damage during launch. Some spacecraft or components for space cannot be built at all on Earth. Examples include ultra-thin mirrors and gossamer structures that can be bent or otherwise adversely affected by gravity forces. Similar and additional constraints limit profitability and flexibility of commercial satellite operations. Taken as a whole, the range of limitations associated with terrestrial construction of spacecraft may represent a significant constraint on the design, capabilities, lifespan, and products of space systems that can be realized.

Researchers and experts for more than 10 years have proposed replacing at least some aspects of this terrestrial architecture with an approach where spacecraft, satellites, and other objects are partially or wholly assembled or manufactured in space. This set of activities is jointly referred to as *on-orbit manufacturing and assembly*. While developments are still at low readiness levels, in recent years, several advances have been made. *On-orbit manufacturing* has recently been demonstrated on the International Space Station (ISS) through additive manufacturing, sometimes referred to as three-dimensional (3D) printing, of small components, such as plastic tools. Many of the technologies and processes required for *on-orbit assembly* are being developed actively in the areas of on-orbit inspection and on-orbit servicing of spacecraft.

A team of researchers at the IDA Science and Technology Policy Institute (STPI) examined the potential implications of on-orbit manufacturing and assembly of spacecraft to supplement the current terrestrial-based approach. We conducted three specific tasks: (1) identify—with quantification to the extent feasible—space missions involving science, exploration, national security, and commercial activity where the payoff of orbital manufacturing and assembly is notable; (2) review the state of the art and future trends of the area from a global perspective; and (3) propose next steps from a U.S. perspective in accelerating progress, from the points of view of both technology and policy.

For the purposes of this project, *on-orbit manufacturing* refers to the fabrication of structures (including 3D printing techniques), and *assembly* refers to aggregation onto a platform of ready-made structures (that were manufactured either on the ground or on orbit). On-orbit manufacture of items to be returned to Earth was not considered.

Payoff from On-Orbit Manufacturing and Assembly

We identified five advantages related to on-orbit manufacturing and assembly that could enable both capabilities for unique science return and potential for cost savings:

1. Ability to deploy structures that cannot be launched from Earth because of constraints imposed by launch vehicle fairing size and shape
2. Ability to achieve increased flexibility and resilience of spacecraft assets enabled by payload additions, replacements, and technology updates while on orbit (made feasible, for example, by the on-orbit presence of a persistent platform)
3. Ability to create cost savings related to carrying more useful mass—less packaging material (structure) related to ruggedization and less platform material
4. Ability to create cost savings through reduction in the number and intensity of ground-based tests of space-bound spacecraft or subsystems
5. Ability to create structures that cannot be created on Earth at all because of constraints imposed by the terrestrial gravitational environment

These capabilities, in turn, could provide dramatic benefit to both scientific advancement and commercial space operations, helping to conceptualize entire new architectures not constrained by the confines of gravity, current manufacturing processes (especially in the case of additive manufacturing), or launch-caused design limitations or structural stresses.

- *In astronomy***,** orbital assembly could enable the construction of telescopes too large to be fully built on Earth and launched into orbit. For exoplanet discovery missions, for example, larger telescopes are required to discover the minimum viable number of exoplanets. If the diameter of the James Webb Space Telescope were to be increased to discover a viable number of exoplanets and current costs extrapolated, its cost could increase by more than a factor of 4. A cost analysis performed by the Jet Propulsion Laboratory (JPL) indicates that on-orbit assembly of such a large space telescope evolved over three launches has the potential to save $12.8 billion in comparison to fielding the same capability using current approaches. On-orbit assembly could also enable the construction of modularized and evolvable instruments with far more capabilities than current and proposed telescopes.

- *In Earth science*, on-orbit assembly could reduce the number of satellite launches for weather and climate observations through the creation of a persistent platform assembled in space. One illustration is the ability to use the persistent platform to replace the A-Train series of six satellites that pass over the same spot on the Earth within a few minutes of each other collecting a variety of measurements. Sensors could be added to the persistent platform on an ongoing basis, enabling faster refresh than is currently feasible. Just as importantly, assembly of multiple payloads (as well as refresh) onto one persistent platform could require fewer launches. For example, if it were possible to deploy six payloads onto the persistent platform using three launches, the potential launch savings could be several hundred million dollars.
- *In solar and space physics*, on-orbit assembly could provide the ability to create or deploy—from a persistent platform—short-term sensors to respond to short-term needs, such as a solar storm.
- *For exploration*, on-orbit or, more generally, in-space manufacturing of small components, tools, and replacement parts from raw feedstocks could reduce the volume and mass of redundant spares that need to be carried and thus could increase resilience, particularly for crewed missions. The ability to recycle unneeded components into feedstock for manufacture of new structures could add further value. On-orbit assembly of lunar and Mars exploration vehicles based on teleoperation, robotics, and autonomy could significantly reduce cost and risk to life associated with astronaut assembly.
- The payoff is not limited to science and exploration alone. On-orbit manufacturing and assembly could also provide payoff for *commercial missions*, especially communication satellites in geosynchronous Earth orbit (GEO). Instead of launching fully assembled satellites as we do today, launching additional antennas from Earth, assembling them as needed on a platform in low Earth orbit (LEO) or GEO, or rearranging them in orbit to compensate for changing requirements could increase not only performance but also revenues. To estimate the potential financial benefits of on-orbit activities, we performed back-of-the-envelope cost calculations based on expert interview inputs. For example, increasing the number of antennas deployed on a single platform from three to six—not feasible when launched as fully assembled satellites—could increase annual revenue by about $80 million per satellite. The presence of on-

orbit infrastructure could also enable more frequent technology refresh. For example, refreshing the communications payload on a traditional satellite after 7 years, in which time, according to the historical trend, new technologies could have increased in performance by a factor of 10, and assuming half of the current revenue charge rates per satellite transponder, could increase revenue by several hundred million dollars over the life of the satellite.

- On-orbit assembly has the potential to provide unique returns for the *national security community*. For reconnaissance missions, for example, orbital assembly could provide the ability to assemble larger apertures than feasible on fully assembled satellites to achieve greater spatial resolution. There is also value in the ability to perform on-orbit assembly on existing platforms, and on platforms designed with standard payload interfaces of sensors to provide increased situational awareness; defensive measures to increase resilience; and updated payloads with increased or different capabilities to enhance flexibility.

State-of-the-Art and Emerging Developments

Having identified the potential benefits of orbital manufacturing and assembly, we reviewed the present status and future prospects for the technical capabilities that can be expected in these approaches from a global perspective. In terms of *on-orbit manufacturing,* additive manufacturing of small components based on polymer feedstock on the International Space Station (ISS) is the only in-space demonstration that has been completed to date. Active research funded by NASA and the European Space Agency in several new areas of on-orbit manufacturing include metals and alloys as feedstock; machines for recycling feedstock from old components; printing electronics; and scaling up to produce larger structures. On-orbit activities continue to benefit from significant investment and progress in terrestrial additive manufacturing.

We envisioned *on-orbit assembly* in the context of this study as being performed robotically with a significant autonomy element. It is likely that some key steps would continue to require a human-in-the-loop approach facilitated by in situ or teleoperations. The development of such capabilities would build upon decades of human-assisted activities in on-orbit inspection, servicing, and assembly that have been conducted on missions such as Skylab, the Space Shuttle, and the ISS. Based on its technical maturity, on-orbit assembly of spacecraft is expected to make a greater impact in a shorter time frame than on-orbit manufacturing.

Key Performers and Funders

NASA is one of two primary U.S. government agencies actively engaged in orbital manufacturing and assembly, both in terms of technology development and as a funding source. NASA has developed a roadmap for ensuring that relevant aspects of additive manufacturing receive appropriate support. The Additive Manufacturing Facility currently operational on the ISS was funded by the In Space Manufacturing Initiative, which is managed by the NASA Marshall Space Flight Center. The NASA Space Technology Mission Directorate (STMD) funds research into both on-orbit manufacturing and assembly through mechanisms such as the Tipping Point program. Orbital manufacturing and assembly activities are also ongoing at other NASA facilities.

DARPA has also made significant investments in developing technologies that are key to orbital manufacturing and assembly. Under the Phoenix program, modular miniature satellites (called satlets) are being developed that can self-assemble on orbit to generate different spacecraft configurations. The Robotic Servicing of Geosynchronous Satellites (RSGS) project aims to increase satellite resilience through development of robotic capabilities for repairing and extending the lifetime of spacecraft in GEO.

In the private sector, both large and small businesses are actively engaged in orbital manufacturing and assembly activities. Within the area of assembly, Space Systems Loral (SSL) is developing the concept of a Persistent Platform in GEO that would operate for 15–20 years, during which time the revenue-generating payloads could be switched out using on-orbit assembly. SSL has also received an STMD Tipping Point award to study robotic assembly of communication antennas. Orbital ATK is developing the Mission Extension Vehicle for servicing spacecraft that, together with other advancements in autonomous operations and robotics, could pave the way for on-orbit assembly. Orbital ATK is also funded under the STMD Tipping Point program to develop a robotic arm for on-orbit assembly.

Within manufacturing, there is less private activity. Using funds from NASA Marshall Space Flight Center, private firm Made In Space developed the 3D printers deployed on the ISS, and also received a STMD Tipping Point award for the development of robotic arms for manipulation and assembly of structures produced by an associated additive manufacturing machine. These Tipping Point projects provide an excellent example of how terrestrially based developments can inform on-orbit approaches. NASA is also funding the firm Tethers Unlimited to look at using compact materials to manufacture large structures in space like solar arrays and antennas.

After reviewing the activities of NASA, DARPA, and several U.S. commercial companies, we estimated that total annual expenditures in the United States on orbital manufacturing and assembly activities were at least $30 million in fiscal year 2016. We estimated the private sector counterpart to these expenditures to be at least $10 million.

Future Activities

Technology

Several areas in both on-orbit manufacturing and on-orbit assembly require significant investment to ensure that the associated benefits can be realized in a reasonable time frame. *On-orbit manufacturing* is relatively immature with the only notable in-space U.S. demonstration having been conducted using polymer materials on the ISS. In our assessment, investment in the following are needed to advance on-orbit manufacturing: (1) expand the range of feedstock materials that can be used for additive manufacturing; (2) develop on-orbit manufacturing approaches for critical satellite structures that cannot be generated using 3D printing; (3) develop procedures for scaling up the physical size of structures that can be manufactured; and (4) characterize the material properties of structures manufactured on orbit.

On-orbit assembly is likely to be realized in a shorter time frame due to progress being made in the related areas of on-orbit inspection and servicing of spacecraft, as well as the sector's ability to significantly leverage terrestrial investments in robotics and automation. For on-orbit assembly to advance, the following developments are needed: (1) teleoperation procedures that will play a key role in robotic assembly; (2) assembly processes for critical spacecraft structures such as telescopes and antennas; (3) sensors and testing techniques to verify that the assembled spacecraft meets its requirements; and (4) modular inter-connections needed for updating and replacing payloads.

To the best of our knowledge, none of the organizations whose representatives we spoke with are collaborating with terrestrial robotic and automation companies. This is important. Unlike the early days of space exploration, where the space sector was ahead of other sectors (and space technologies were *spun-out* to other sectors), the space sector today is frequently at the receiving end of terrestrial developments (with technologies *spinning in*). There is a need for greater leveraging by the space sector of terrestrial capabilities which, in sectors such as automobiles and computing, are being funded at levels that may be orders of magnitude higher than space.

Policy

In addition to continuing to invest in the research and development required to advance on-orbit manufacturing and assembly, the United States can facilitate commercial investment in a number of ways, including development and distribution of community tools, development of community standards, and provision of infrastructure such as on-orbit platforms and launch opportunities. But more important than any individual investment—which could be made by the private sector given its equities in the system—the government has an important role with respect to ensuring activities across the ecosystem are coordinated, and to providing the private sector with incentives for investment, including ensuring a clear legal regulatory framework in which to operate.

Main Conclusions

We find that many space missions could benefit from on-orbit manufacturing and assembly including astronomy, Earth observation, space exploration, telecommunications, and national security. There are also a number of different types of performance enhancements enabled by on-orbit manufacturing and assembly including science return, quality and quantity of data, asset re-configurability, and mission resilience and flexibility. The applications that are likely to see the most substantial impacts are space telescopes and communications satellites. On-orbit assembly provides a viable pathway for the deployment of the next generation of space telescopes that cannot be launched on today’s rockets, while providing potential cost savings over the current approach. Communications satellites are expected to generate increased revenues through the deployment of larger numbers of antennas and refreshing the payload technologies through on-orbit assembly.

In the coming years, on-orbit assembly is expected to mature more rapidly as key aspects of the approach are being advanced by developments in commercial on-orbit servicing. On-orbit manufacturing is more nascent. Both areas could benefit from better leveraging of the considerable investment in terrestrial activities in additive manufacturing, robotics, and automation. The federal government could facilitate development of on-orbit manufacturing and assembly in several ways, such as providing funding, infrastructure, and tools, and through development of standards and policy.

Contents

1. Introduction

In the history of spaceflight, almost all spacecraft have been manufactured and assembled on the ground, then integrated into a launch vehicle for delivery into orbit. This approach imposes significant limitations on the size, volume, and design of payloads, as they must be accommodated within the fairing of a single launch vehicle. In particular, fairing diameter limitations restrict the size of instruments that can be fielded in orbit for science and national security missions. In turn, these constraints place definite limits on the capabilities of space borne payloads. For example, NASA's Hubble Space Telescope has an aperture diameter of about 2.4 meters (m) that has allowed it to survey about 1% of the sky. The next telescope mission, the James Webb Space Telescope (JWST), is limited by current launch vehicles and folding mechanisms to a 5.6 m aperture diameter that is projected to allow it to survey approximately 5% of the sky. In addition to filling the largest current launch fairings, the on-orbit deployment of JWST will involve 400 individual steps that must all work perfectly, posing considerable risk to the mission. It is estimated that a 12-meter diameter telescope aperture is required to image enough exoplanets to make a statistically meaningful determination of whether there is biological life on other worlds. A telescope of this size cannot be deployed into orbit today using a single launch.

A similar situation exists for imaging the Earth from space for scientific, commercial, or national security missions in which the spatial resolution that can be obtained currently is limited by the size of apertures that can be launched into orbit.

Communications satellites face two important limitations. First, launch vehicle fairings constrain both the size and number of antennas that can be accommodated on a single satellite. Second, the payload technology of communications satellites advances in capability by a factor of 10 every 7 years, like Moore's Law for computer processing speed. Because satellite operators have no choice but to launch fully formed, unchangeable satellites, the technological capability at the end of 15 years of operation of one of these satellites is therefore about a factor of 100 less than new, updated technology, representing a significant lost opportunity for generating additional revenue.

Another type of limitation associated with the terrestrial construction of spacecraft is that it requires all the components of each spacecraft to be ruggedized to withstand the harsh launch environment, which includes severe vibrations, acoustics, acceleration loads, and thermal loads. Ruggedization processes impose penalties in terms of mass and size that ultimately limit payload capabilities and increase launch costs. These penalties are further compounded by the need to include backup systems to provide contingency against damage during launch. In addition, extensive pre-launch testing of the hardened components consumes some of the overall spacecraft development schedule and the margins imposed on these tests increase program cost and schedule risk.

Some systems or their components simply cannot be built on Earth. A National Aeronautics and Space Administration (NASA) Goddard Space Flight Center (GSFC) report cites the International Space Station (ISS) as an example of an installation that was too large to have been assembled, tested, and launched from the ground at once (NASA GSFC 2010). At the component level, some space-based objects such as ultra-thin mirrors, gossamer structures, reflectors, trusses, and panels simply cannot be made in a gravity environment. The ISS solar arrays, for example, span over 3,500 square meters and would warp under Earth's gravity if fully assembled on the ground (Hoyt 2013).

Taken as a whole, the range of limitations associated with terrestrial construction of spacecraft may represent a significant constraint on the design and capabilities of space systems that can be realized currently. Figures 1 and 2 illustrate how these limitations affect science return and communication satellite revenues.

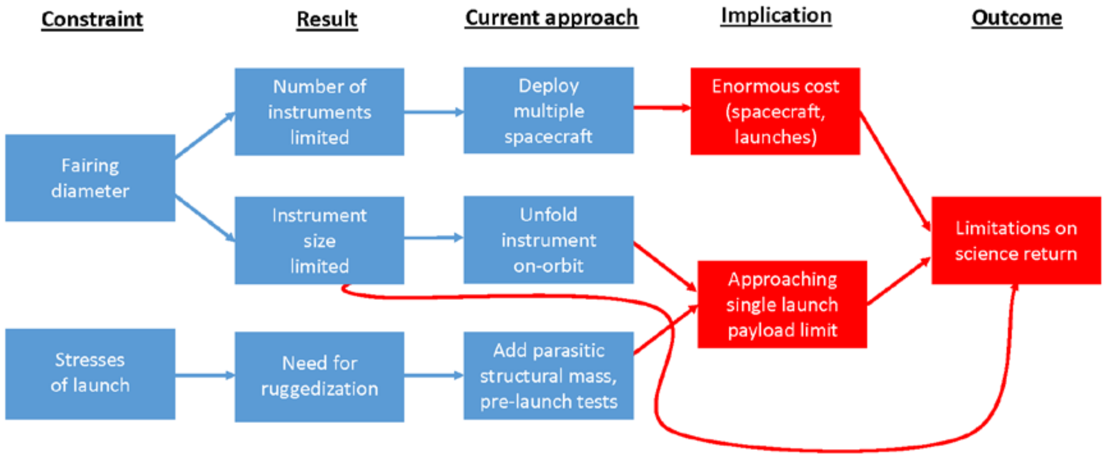


Figure 1. How the Current Approach to Deployment of Space Instrumentation Limits Science Return

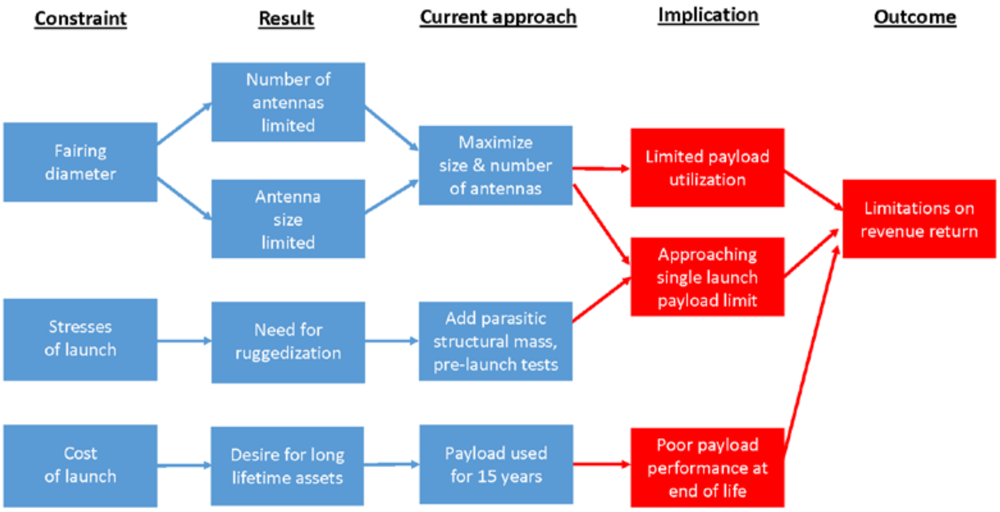


Figure 2. How the Current Approach to Deploying Communications Satellites Limits Revenue Return

A team of researchers at the IDA Science and Technology Policy Institute (STPI) conducted an overview of the potential implications of on-orbit manufacturing and assembly of spacecraft (also referred to as orbital manufacturing and assembly) to supplement the current terrestrial-based approach. We focused on three aspects in particular: identification (with quantification to the extent feasible) of areas of science, space exploration, and commercial activity where the payoff from orbital manufacturing and assembly is notable; review of the state-of-the-art in this sector; and potential next steps to make the architecture feasible, from the perspectives of both technology and policy improvements.

Defining Terms and Scope

Manufacturing: fabrication of structures (including, but not limited to, printing techniques). Focus on additive manufacturing.

Assembly: aggregation using ready-made structures (that are manufactured either on the ground or on orbit).

Note: On-orbit manufacture of items to be returned to Earth is not considered in this report. Analysis related to this activity is available in other STPI reports (e.g., Private Space Station report). We also exclude surface manufacturing and focus primarily on on-orbit

The sidebar defines key terms of interest and scope of the analysis, which was conducted by collecting information through interviews along with reviews of online information and the archival literature through four inter-related tasks:

1. Identify current and future spacecraft missions that could benefit from on-orbit manufacturing and assembly

2. Evaluate benefits of on-orbit manufacturing and assembly
3. Evaluate trends in and challenges to on-orbit manufacturing and assembly
4. Identify steps that the federal government could take to facilitate the development of on-orbit manufacturing and assembly

The layout of the report is as follows: Chapter 2 reviews current and future space missions to determine whether any may benefit significantly from use of on-orbit manufacturing, on-orbit assembly, or both. Four case studies are presented to quantify the potential benefits for specific missions. To provide a better understanding of the time scales that may be involved in maturation of on-orbit approaches to construction of spacecraft, we describe the development trends and challenges to on-orbit manufacturing and on-orbit assembly separately in Chapters 3 and 4, respectively. In Chapter 5, we propose steps that the federal government could take to facilitate the continued development of on-orbit manufacturing and assembly of spacecraft.

A list of the organizations and individuals that participated in the interviews is provided in Appendix A.

2. Exploring Benefits of On-Orbit Manufacturing and Assembly

Spacecraft are used for a variety of missions, including space science, Earth observation, telecommunications, human and robotic exploration of space, and national security. In the future, this mission set is likely to both increase in number and intensity as the number of players engaged in space-based activities expands (Lal et al. 2015). The first step in understanding the potential contributions that on-orbit manufacturing and assembly may make to the space enterprise is to identify specific missions that may benefit from advances in these approaches. A useful starting point is to consider the constraints imposed on missions by the current operational paradigm of launching systems that have been manufactured and assembled on the ground. It is also important to consider if and how the on-orbit paradigms may enable entirely new space capabilities and missions.

In this chapter, the main space missions are reviewed in the context of how they may benefit from on-orbit manufacturing and/or assembly approaches. Several examples of quantitative analysis are presented to illustrate potential benefits. In these analyses, the costs involved in developing the on-orbit manufacturing and assembly capabilities are not included. The primary purpose of this analysis is to evaluate mission benefit of these approaches.

A. Space Sciences

In the U.S. space science communities, surveys are conducted every 10 years to establish the highest priority missions. These decadal studies are conducted and published by the National Research Council (NRC) in four areas: (1) astrophysics and astronomy; (2) Earth science; (3) planetary science; and (4) heliophysics. We used the NRC's decadal studies to identify representative space sciences missions that are enabled or made feasible at a lower cost through application of orbital manufacturing and assembly approaches. To illustrate, we provide specific examples through case studies for mission areas where most benefit is identified.

In the United States, space-based science missions are conducted mainly by NASA, and they involve the use of in situ instrumentation to study the Earth's surface, the near-Earth environment, the solar system, and deep space. Many of the instruments employed function through the collection of electro-magnetic radiation across various regions of the spectrum. Since this collection is always being performed at very large distances from the originating sources (especially in the area of astrophysics and astronomy), the instrument collection area, or aperture diameter D_A, is a critical parameter that determines the signal strength that can be detected and the spatial resolution that can be achieved. For example, for an optical telescope, the light-gathering power is proportional to $(D_A)^2$. Hence, larger instruments detect weaker light sources and require less observation time, thereby increasing the number of observations that can be made and the time-resolution of the results. The angular resolution, or the ability of a telescope to distinguish small details of an object, is proportional to $1/D_A$. Hence, larger instruments also provide finer resolution of sources.

Two significant constraints limit the aperture size that can be employed in space science missions. First is the fairing size of the launch rocket. The largest launch vehicles today, the Atlas V 551 and the Ariane-5, have a fairing diameter of 5.4 m and so cannot accommodate a telescope with a larger diameter without employing schemes to deploy expanded structures. The NASA Space Launch System (SLS) program includes options to develop future vehicles with fairing diameters ranging from 5 to 10 m. While the deployment of such systems would alleviate many of the current launch limitations, these systems are far from being developed, and involve significant technical and funding risk.

A second challenge in the current approach to building large space instruments concerns the need to design and test instrumentation on the ground under sea-level gravity (1-g) conditions for their operation in the microgravity environment of orbit. This process requires careful testing and modeling to demonstrate that the instrument performance at 1 g will extrapolate to the performance required in 0 g. Assembly of instrumentation on-orbit in the 0-g environment would obviate the reliance on modeling gravitational effects on structures that have very fine tolerance requirements.

Any new technological approach that would enable the fielding of much larger instruments for space sciences has the potential to significantly enhance the quantity and quality of information that can be generated from these missions. In the following subsections, we review the four subsets of space sciences and provide specific examples of how on-orbit manufacturing and assembly approaches may significantly enhance certain space missions.

1. Astrophysics and Astronomy

Astrophysics and astronomy involves the study of physical properties and processes of planets, stars, and galaxies from the near-Earth environment, including from the ground, LEO, or GEO. Observations are conducted across the electromagnetic spectrum, including ultraviolet, visible, infrared, radio wave, gamma ray, and x-ray ranges. The most recent decadal study in astronomy and astrophysics recommended three large space-based missions—Wide Field Infrared Survey Telescope (WFIRST), Laser Interferometer Space Antennae (LISA), and International X-ray Observatory (IXO)—in addition to ground-based missions, technology development in specific areas, and other small projects (NRC

2010). WFIRST is currently being built, has a 2.4-m diameter, is planned for launch to GEO in the early 2020s, where it will remain for the duration of its expected 6-year mission (NASA 2016b, NASA GSFC 2016). WFIRST is being developed in parallel to the Restore-L spacecraft (see Chapter 4, Section B) in a way similar to how the Hubble Space Telescope (HST) was developed in parallel to the Space Shuttle, so WFIRST is expected to be fully serviceable on orbit, according to an interview with an industry expert. LISA and IXO were recommended by the 2010 decadal study, but are not currently being pursued. LISA was to consist of three telescopes in a triangular configuration to study gravitational waves, while IXO was to have a 3-m diameter mirror and a 20-m focal length when unfolded into its final configuration on its flight to Sun-Earth Lagrangian point L2 (NRC 2010).

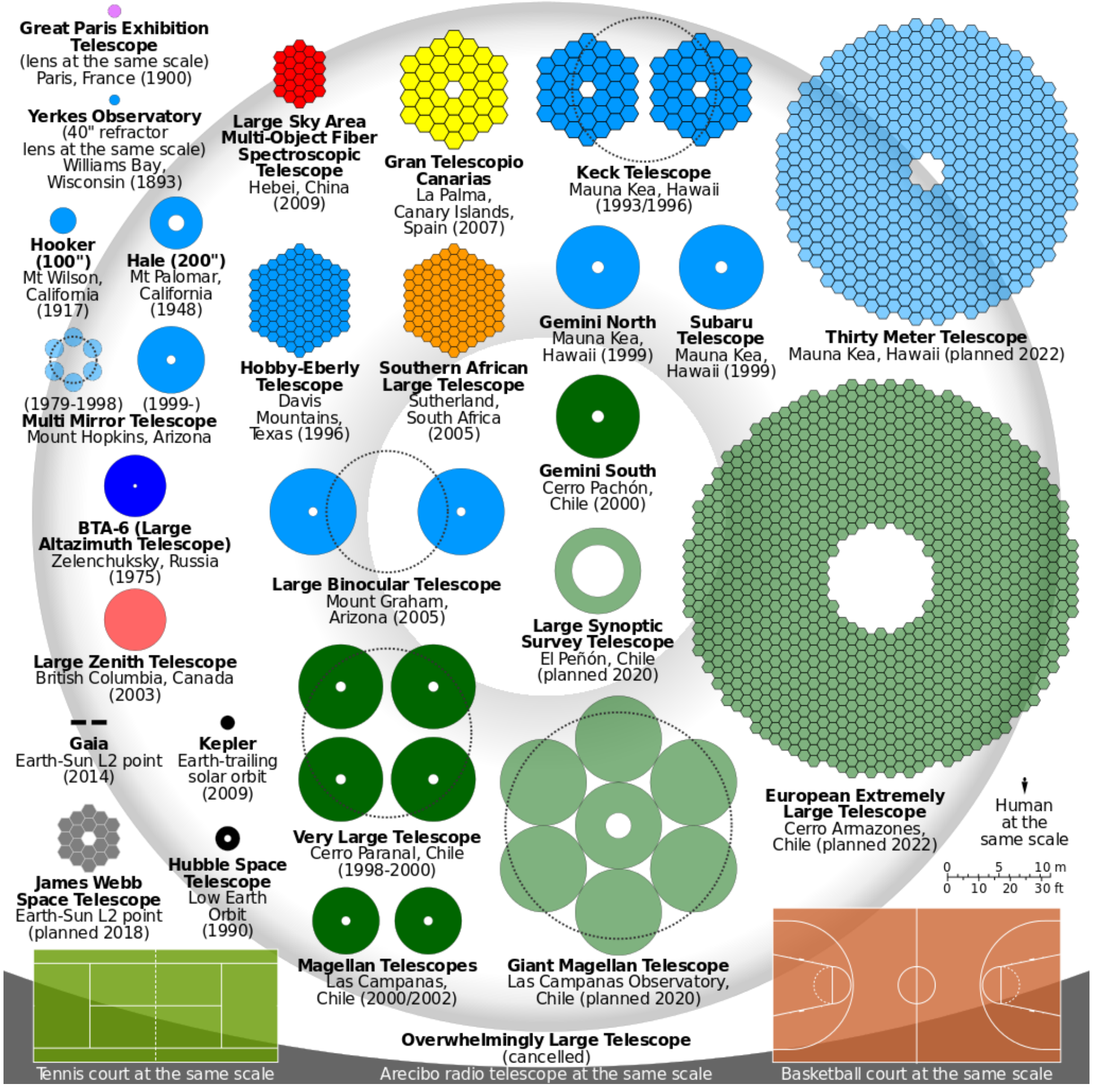
The four missions currently formulated as input to the next astrophysics and astronomy decadal survey are X-Ray Surveyor, Far-Infrared Surveyor, Habitable Exoplanet Imaging mission (HabEx), and Large Ultraviolet Optical Infrared (LUVOIR). Designs thus far accept the size constraints of a launch vehicle. The X-Ray Surveyor is the successor to the Chandra X-Ray Observatory and, like the IXO, has a 3-m diameter (Gaskin et al. 2015). The Far-IR Surveyor has a 4 × 6-m off-axis primary mirror that will fold into the 5-m launch fairing (Armus et al. 2015). HabEx will incorporate either coronagraphs or starshades to search for biosignatures on rocky exoplanets (NASA Jet Propulsion Laboratory [JPL] 2016). It is possible that the starshade could be manufactured on orbit. HabEx can have a 4-m mirror and fit in an SLS fairing (Stahl et al. 2013). The LUVOIR mirror will be between 8 and 19 m in diameter; a concept to fit the 8-m mirror into the 8- or 10-m SLS fairing has already been proposed (Stahl et al. 2013). Of these four mission concepts, telescopes having diameters significantly larger than available launch fairings would benefit from on-orbit assembly.

Two case studies follow that illustrate the science and revenue return to be gained from on-orbit manufacturing and assembly for astrophysics and astronomy missions. These cases are presented as they represent the clearest and most significant benefits that we identified in our analysis.

Case Study: Increased Science Returns from a Space Telescope

High-definition space telescopes (HDSTs) are very large, space-based observatories with a number of primary missions, including: (1) characterizing exoplanets and searching for life on exoEarth candidates through the use of spectroscopic bio-markers; (2) understanding the origin and evolution of the universe through stellar population surveys; and (3) determining the distribution of dark matter and dark energy.

Figure 3 compares the physical size of a number of terrestrial and space-based telescopes. It is clear that the four space-based telescopes, HST, Kepler, Gaia, and JWST, are all smaller in size than the largest current ground-based facilities (e.g., the Keck Telescope in Hawaii and the Very Large Telescope in Chile) and significantly smaller than several terrestrial telescopes that are in planning (e.g., the Thirty Meter Telescope in Hawaii and the European Extremely Large Telescope in Chile).



Source: Ventrudo (2015).

Figure 3. Variation of Mirror Size Used in Telescopic Observations

Space-based telescopes are limited in three important ways: (1) *physical size* by the launch vehicle fairing; (2) *mass* by the maximum payload that can be accommodated on a single launch; and (3) *overall cost*, which is significantly higher than equivalent terrestrial capabilities.

We use the mission involving the search for exoEarth candidates to illustrate HDST requirements. Analysis based on the binomial theorem conducted by the Association of Universities for Research in Astronomy (AURA) shows that at least 30 candidates must be characterized to infer statistically meaningful conclusions about the prospects for biological life on other planets (AURA 2015). The same analysis showed that telescope aperture diameter is the most important variable in determining the number of candidates that can be characterized, and the relation is plotted in Figure 4. Data points are included in Figure 4 for HST and for JWST that is the next NASA HDST mission, which is planned to be launched in 2018. With an aperture diameter of 5.6 m, JWST is expected to identify about 10 exoEarth candidates. To advance the search for exoEarth candidates beyond JWST to a level of stronger scientific rigor, a significant increase in telescope aperture diameter is required on future HDST missions. Figure 4 shows that this diameter is about 12 m.

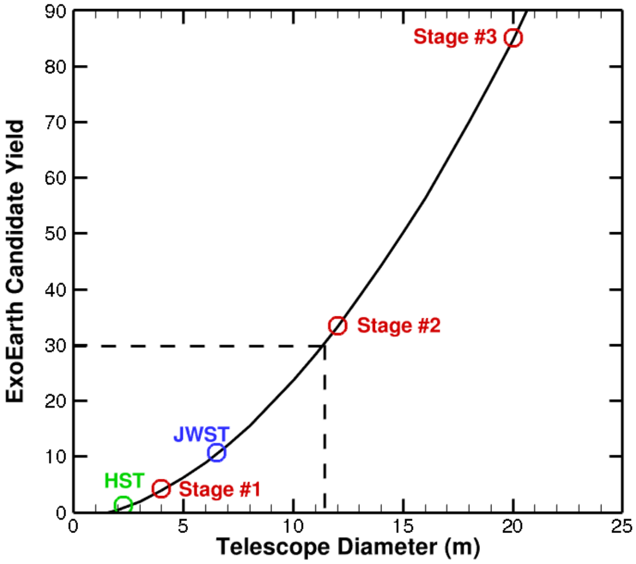
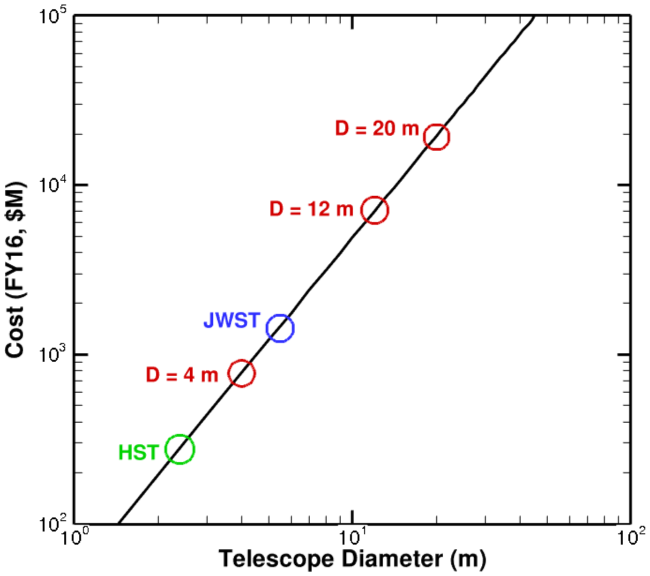


Figure 4. Exoplanet Yield as a Function of Telescope Diameter

The JWST aperture diameter is approaching the size limit for what can be accommodated within current launch vehicle fairings; even then, this size necessitates use of a complicated folding arrangement, with all the associated risks and ground testing requirements. While larger launch fairings are being considered in the development of the SLS (NASA 2016a), significant growth beyond current capabilities is both technically challenging and expensive.

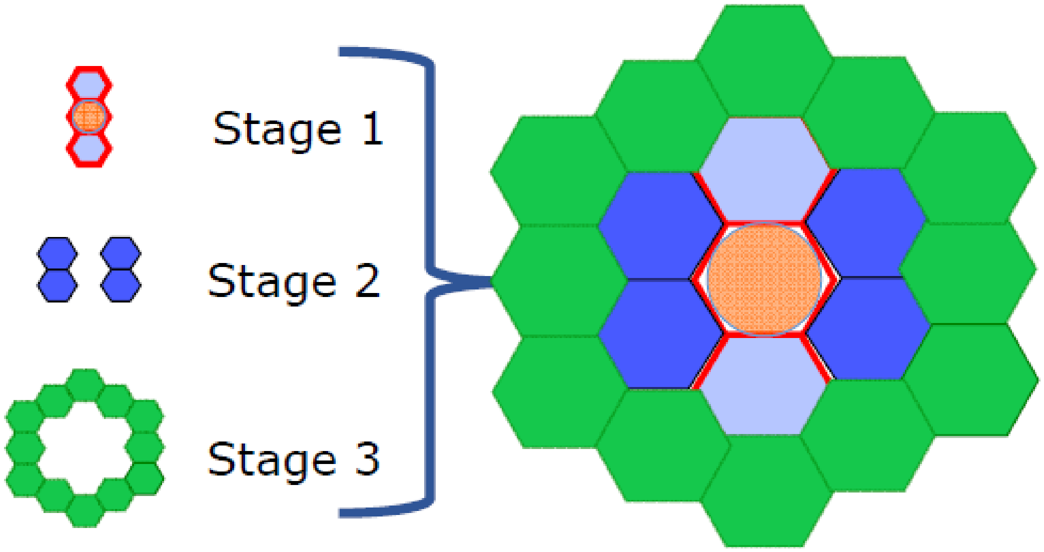
Mission cost represents a second limitation on the current paradigm for deployment of HDSTs. As described in (Stahl et al. 2013), and based on a review of many space telescope programs, the cost of a space telescope scales with the square of the telescope diameter. This relation is shown in Figure 5. Note that this is just the cost of the telescope that is typically 15 to 30% of the total cost of the entire space observatory. The rest of the cost involves the platform, mission sub-systems, and ground infrastructure. By cross-referencing Figures 4 and 5, it becomes clear that a desire to increase the telescope diameter to 12 m, which is the requirement to detect the minimum viable number of exoplanets, would increase the cost over JWST by more than a factor of four (from $9 billion to about $36 billion).



Source: Adapted from Stahl et al. (2013).

Figure 5. Telescope Cost as a Function of Telescope Diameter

On-orbit assembly provides a potential pathway to address the size and cost challenges of next-generation HDSTs. For example, consider the three-stage evolvable space telescope concept described in Polidan et al. (2014) and shown schematically in Figure 6. The idea is to assemble a large telescope in space using large hexagonal elements that are 4 m across from one flat side to another. The telescope would evolve over three launches that are separated by several years representative of budget cycles for such missions. In the first stage, the central circular secondary mirror, and two hexagon elements that form the primary mirror assembly are launched in a single stack and assembled on orbit to form an asymmetric aperture of 4.5 × 12 m. In the second stage, four additional hexagon elements are launched in a single stack, and assembled on orbit to form a symmetric aperture of 12 m in diameter. The third stage would again be separated by one full budget cycle and would launch 12 additional hexagons that would be assembled on orbit to the existing structure in order to complete a telescope with an aperture diameter of 20 m.



Source: Polidan et al. (2014).

Figure 6. Three-Stage Evolvable Space Telescope Concept Leading to 20-m Aperture Diameter

Case Study: Decreased Cost of Building a Large Space Telescope

We use the evolvable telescope of Polidan et al. (2014) to compare the costs associated with the traditional approach (i.e., that currently being used for JWST) and the on-orbit assembly approach. The costs associated with building each of the three telescope stages in the traditional manner are estimated using a straightforward application of the model of Stahl et al. (2013) to obtain the following values:

- Single Launch Stage 1: $3.1 billion
- Single Launch Stage 2: $6.5 billion
- Single Launch Stage 3: $18.0 billion
- Total Cost (traditional): $26.6 billion

The analysis assumes that each stage is launched on a single booster and deployed in the traditional manner. Consistent with Stahl's model, the above costs are for construction of the Optical Telescope Assembly (OTA) only, not the overall mission cost, and not inclusive of launch costs.

It is important to recognize that only the Stage 1 configuration can actually be packed into the fairing of any existing heavy-lift launch vehicle, with a 5-m fairing. Stage 2 would require the SLS Block 1B 8-m fairing. Stage 3 would be too large to fit into even the SLS Block 2 10-m fairing. This limitation illustrates a compelling advantage of the on-orbit assembly approach—it enables use of telescopes that are impossible to launch any other way.

Estimating the cost of building an evolvable space telescope is difficult as the development of on-orbit assembly technology is required and cost models for this new paradigm are not available. One approach might be to adapt the Stahl et al. model, but, because that model is based on telescopes that are pre-assembled and stowed on the ground, exactly how to adapt the approach is not clear. Instead, a model was developed (correspondence with Dr. Robert Laskin, NASA Jet Propulsion Laboratory, December 2016) in which data was used from a large telescope testbed built at NASA JPL in the 2007–2012 time frame. The testbed was built as part of the Advanced Mirror Development (AMD) project funded by the Department of Defense (DOD). It was a 6-m diameter OTA whose primary mirror consisted of 1.35-m (point-to-point) hexagonal mirror segments. The mirror segments themselves were engineering model class hardware as was the laser metrology system that interfaced to the segments. Hence, the mirrors and metrology were flight-like and built to withstand launch loads. The OTA structure was built of flight-quality carbon fiber reinforced polymer composite, but was not designed with launch loads or deployment in mind. Nonetheless it was representative of the sort of structure that might be carried to orbit in pieces and then assembled. It is assumed that assembling a large telescope on the ground with humans is not that different from assembling one on orbit with telerobotics, so long as the proper grappling fixtures have been designed into the constituent parts. The AMD cost data was modified somewhat to account for the fact that the testbed primary mirror was not fully populated with actual mirror segments (15 segment simulators were used). The costs of the mirror and metrology electronics were also modified to reflect space-rated versions.

With the above methodology, the extrapolated flight assembled version of the AMD testbed cost was input into Stahl’s model (correspondence with Dr. Robert Laskin, NASA Jet Propulsion Laboratory, December 2016). It is found to come in at less than one third the estimated cost of the traditional deployed version. Allowing for additional expense for making all the parts grapple-ready and factoring in robotic efficiency versus human efficiency might lead one to believe that the on-orbit assembly approach results in OTAs that are approximately half the cost of the traditional approach. At any rate the savings would be large and would be even more striking as OTA size increases. So it seems reasonable to divide the previously stated Stage 1–3 numbers in half for on-orbit assembly and then add the cost of the robotic infrastructure required to perform the assembly. It is estimated that an approach with three robotic arms capable of assembly of Stage 3 would cost on the order of $0.5 billion, a small fraction of the cost of the telescopes themselves.

The bottom line finding of this analysis is that on-orbit assembly of Polidan’s three-stage evolvable telescope would cost about $12.8 billion less than the traditional approach to deploying telescopes (correspondence with Dr. Robert Laskin, NASA Jet Propulsion

Laboratory, December 2016). It is also important to note that deploying the telescope using the traditional approach is not even feasible as it would require a launcher that is larger than any of the options being considered in the SLS program.

2. Earth Science

Earth Science involves making observations of the Earth from orbit to collect information for a variety of purposes, including weather, climate, agriculture, the oceans, and basic science (not to mention commercial sale of Earth images and image-based data-analytic products). The Earth science decadal study completed in 2007 recommended 13 LEO missions and two GEO missions (NRC 2007). The next Earth science decadal study will be completed in late 2017 (National Academies of Sciences, Engineering, and Medicine 2016).

Much of the instrumentation used for Earth science missions involves collection of electromagnetic radiation. Relative to astrophysics and astronomy, the distances here are smaller, so there is less need to significantly increase instrument size. However, for detailed study of weather and climate phenomena, there is a desire to gather several different sets of measured properties simultaneously for a single event of interest, such as a strong storm. The current approach to making such measurements is the so-called *A-Train*: a constellation of six LEO satellites, mostly funded by NASA, but including participation from the European Space Agency (ESA), the Japan Aerospace Exploration Agency (JAXA), and the Canadian Space Agency. The satellites pass over the same spot on the Earth within a few minutes of each other, collecting a variety of measurements. Each of the six A-train spacecraft was launched separately. A new approach involving orbital manufacturing and assembly would co-locate all of the instruments on one large, persistent platform. The entire spacecraft would be too large for a single launch, so its integration would be enabled by on-orbit assembly. The oldest A-train elements date back to 2002. Given the significant advances in spacecraft since that time in terms of increased performance and miniaturization, it is reasonable to assume that six instruments with similar capability to the current A-train could be placed into orbit along with the host platform on three launches. The number of launches would therefore be reduced by three, representing an estimated savings of $600 million. Of course, these savings would be offset by the cost of the infrastructure needed to assemble payloads onto the platform on orbit, which are estimated to be on the order of $10 million. The approach described here could also facilitate the on-orbit interchange of instrument payloads every few years onto the modular platform.

3. Planetary Science

Planetary science involves the study of planetary bodies using instrumentation that has been transported to the vicinity of the planet of interest. The instrumentation may be accommodated on a spacecraft that is either in orbit around the planet, is following a fly-by trajectory, or is on a rover on the planet's surface. In general, planetary observation from an orbiting spacecraft involves essentially the same mission as remote sensing for Earth sciences. Potential benefits of on-orbit assembly that would be conducted prior to transit of the spacecraft to a planet are therefore similar and include the ability to deploy larger apertures for higher resolution imaging and co-location of several different instruments onto one platform to enrich the scientific data sets.

A number of missions were recommended by the planetary science decadal survey. The lowest-cost mission was the Mars Trace Gas Orbiter, now the ExoMars Orbiter, run by ESA. Suggestions for medium-cost missions included Asteroid Sample Return (now known as OSIRIS-REx for Origins, Spectral Interpretation, Resource Identification, Security-Regolith Explorer), Lunar South Pole Aitken Basin Sample Return, Saturn Probe, Trojan Tour and Rendezvous, Venus In Situ Explorer, Io Volcano Observer, and Lunar Geophysical Network. Large-cost mission suggestions included Mars Astrobiology Explorer-Cacher (now known as Mars 2020), Jupiter Europa Orbiter, and Uranus Orbiter and Probe. Of these eleven missions, five have power or mass constraints. Power constraints tend to stem from the fact that there is less solar energy in deep space, requiring the use of (sometimes several) advanced radioisotope generators. These power constraints, combined with long distances from Earth, also limit the data downlink capabilities of planetary spacecraft. Solar sails, solar arrays, concentrators, and radiators could be manufactured on-orbit to avoid launch fairing constraints or in-transit to eliminate the need for redundancies and to reduce power constraints. Mass constraints derive from launch constraints, and could be resolved in a manner similar to the construction of the evolvable space telescope (see subsection A.1 on astrophysics and astronomy), where large mission components are launched and assembled in LEO before being deployed to deep space. Finally, in situ resource utilization (ISRU) combined with additive manufacturing may aid the two sample return missions by reducing the mass of components that must be launched from Earth and transported to the final destination. For example, the Mars Science Laboratory that delivered the Curiosity rover to the surface of Mars in 2011 had a total spacecraft mass of 3,839 kilograms (kg) and a launch cost of $500 million ($130,000 per kilogram). It is first necessary to manufacture components equal to the mass of the 3D printer; for example, the Additive Manufacturing Facility (AMF) 3D printer on the ISS weighs 45 kg. After that, every additional 7.7 kg of components manufactured from in situ resources saves about $1 million. These savings are not large enough to matter for deep space missions. However, with volume and mass severely constrained on any Mars transportation spacecraft, the real benefit of ISRU combined with additive manufacturing is in the fabrication of useful structures that would not be available without sending additional spacecraft to the planet (NRC 2011).

4. Heliophysics

Heliophysics, sometimes referred to as solar and space physics, is the study of the Sun and the influence it exerts on the space environment from its surface to Earth to the edge of the solar system. Heliophysicists investigate the nature of the solar wind, energetic particles, plasmas, and magnetic fields within the heliosphere. While some imaging is involved, most heliophysical measurements are conducted using a variety of relatively small instruments such as spectrometers and plasma probes. Such devices do not suffer from the weak signal challenges experienced by imaging instruments such as telescopes. Physical size is therefore much less of a limitation for this class of instrumentation. Satellites involved in heliophysics missions often work under intense solar radiation in highly elliptical orbits.

The most recent decadal survey in heliophysics included four space missions: Interstellar Mapping Probe (IMAP), Dynamical Neutral Atmosphere-Ionosphere Coupling (DYNAMIC), Magnetosphere Energetics, Dynamics, and Ionospheric Coupling Investigation (MEDICI), and Geospace Dynamics Constellation (GDC) (NRC 2012b). IMAP will study the boundary between the heliosphere and the interstellar medium (McComas et al. 2013). It is a low-cost mission and a direct follow-on to Interstellar Boundary Explorer (IBEX); it consists of a small spacecraft (with a cost less than $10 million in fiscal year 2010) at the L1 Sun-Earth Lagrangian point and runs on solar power. It points toward the Sun with an antenna facing Earth for data transfer. The DYNAMIC mission consists of two spacecraft in LEO with instruments that can measure energy inputs in the atmosphere-ionosphere-magnetosphere system from the Earth itself. MEDICI is a pair of spacecraft in high (eight times Earth's radius) polar orbits with a suite of instruments that comprehensively measure the plasmasphere, ionosphere, and thermosphere. The high orbit avoids regions of most intense radiation. GDC is a set of six LEO satellites in high-inclination orbits that provide full global coverage every 90 minutes and inform how the Earth's atmosphere absorbs solar wind energy (NRC 2013).

Heliophysics missions employ relatively small instruments for which orbital manufacturing and assembly will likely have limited impact. Imaging instruments used in these missions would benefit from the same type of advantages from on-orbit assembly as discussed above for Astronomy and Earth Science; specifically, the deployment of larger apertures and the co-location of many instruments.

B. Space Exploration

Of most relevance to the potential benefits of orbital manufacturing and assembly is the ISS. The station is too large to have been assembled, tested, and launched from the ground at one time (NASA GSFC 2010). As previously mentioned, the large solar arrays would warp under Earth's gravity if fully assembled on the ground (Hoyt 2013). Individual subsystems and modules were tested on the ground and designed to be attached to one another on orbit (NASA GSFC 2010). The station was built between 1998 and 2011 with components from over 100 Russian and U.S. launches and over 160 spacewalks spanning over 1,060 hours (NASA 2016d, e).

For missions requiring very large spacecraft (especially, the Mars surface mission) on-orbit assembly may be highly beneficial (NRC 2012, 41, Technology 7.6.2a). Successful development of autonomous, robotic on-orbit assembly approaches would reduce the cost and risks associated with the many hours of astronaut space-walks conducted during construction of the ISS (NRC 2012, 33, Technology 4.3.2, Dexterous Manipulation). Advances in docking and interfaces would allow for precision and reliability during on-orbit assembly (NRC 2012a, 55, Technology 12.3.1, Deployables, Docking and Interfaces). For example, consider the hourly cost of an astronaut on an existing on-orbit assembly facility such as a space station. We used a figure of $20 million per person for potential future launch costs, which includes the cost of the capsule. The $20 million figure was derived from ongoing STPI research into the cost of a private space station. Assuming a 5-hour work day (equivalent to a 35-hour work week) and a 180-day stay on the space station, the amortized launch cost of astronaut time is about $22,000 per hour ($20 million for an astronaut launch divided by 900, the total number of hours worked over 180 days given a 35-hour work week). Adding the launch cost of consumables, $80,000 per astronaut day, divided over the astronaut's work hours, it would require over $38,000 per hour for astronaut time just to cover costs. It took more than 1,000 hours of astronaut time to assemble the ISS. Assuming a Mars exploration vehicle would be significantly smaller and less complex, we estimated it would require only 100 hours of astronaut time with the total cost of crewed assembly coming to about $3.8 million, which is negligible compared to the total mission cost. The more important value added from robotic on-orbit manufacturing and assembly here is the elimination of risk to human life by avoiding astronaut extra-vehicular activity (EVA).

Human missions beyond Earth's Moon (asteroid in native orbits, Mars moons, and Mars surface missions) will require on-orbit assembly of both cargo and crew spacecraft, the masses and volumes of which are both too large to fit on even the largest planned launch vehicles, the SLS Block 2B. By launching the cargo payload in a separate module that is joined to the solar electric propulsion module on orbit, and by launching a separate crew module that is joined to a fully fueled propellant tank on orbit, the overall mission can be accomplished. Without on-orbit assembly, human missions beyond the Moon would be impossible.

Increasing mission duration is associated with increasing risk of component failure that may be mitigated by on-orbit manufacturing. In addition, mass and volume are precious commodities for such long-duration missions. In-space manufacturing of tools and spare parts could be achieved by carrying raw feedstock in volumetrically efficient containers (Do et al. 2016). The ability to generate a wide range of tools and spare parts on demand would significantly reduce the mass and volume associated with transporting a wide range of such objects, of which only a small fraction may actually be needed in the mission. Clearly, these advantages are greater for crewed missions.

On a side note, long-term stays on the surfaces of Mars and its moons expose humans to the deleterious effects of radiation. Currently, there are few viable methods of protecting humans from harmful radiation other than mass shielding. Construction of sufficient mass shielding on the surfaces of other bodies would benefit from surface manufacturing from raw feedstock (as mentioned above) or from in situ resource utilization (NRC 2012a, 41, Technology 7.1.3, ISRU Products/Production, and Technology 7.6.2, Construction and Assembly). Similarly, for missions requiring descent and ascent vehicles (lunar sorties, the moons of Mars, and Mars surface missions), construction of landing and launch pads is of interest. In this case, sintering would solidify and strengthen the dusty regolith (NRC 2012a, 41, Technology 7.6.2, Construction and Assembly; Hintze, Curran, and Back 2009; NASA 2015c). Especially for landing sites, sintering reduces the chances of secondary ejecta (pieces of regolith thrown from the surface upon impact) damaging exploration systems. Furthermore, permanent facilities on Earth's Moon and Mars may not be possible without development of in situ manufacturing and assembly methods.

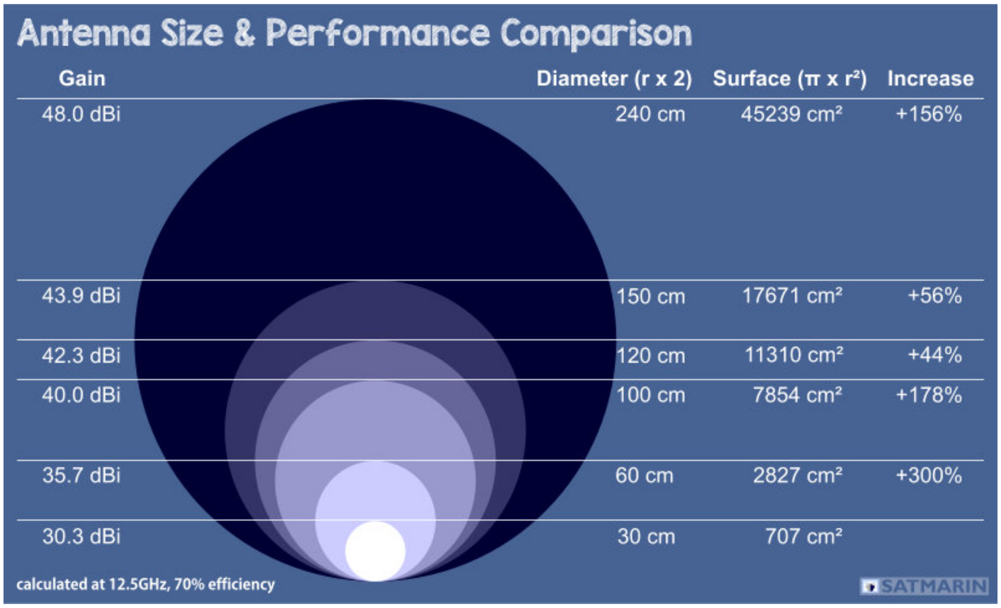
C. Space-Based Communications

Telecommunications involves the transmission of information through cables, by radio waves, and other forms of electromagnetic radiation. The telecommunications market generates annual revenues in excess of $1.4 trillion worldwide (*Statista* 2016) that is dominated by use of land lines and through-the-air radio wave transmission. It also includes a sizeable space-based sector that is used primarily for long-distance transmission and is largely run by commercial enterprises. The space telecommunications sector generated commercial revenues in excess of $127 billion in 2015 with an annual growth rate of 4% (Tauri Group 2016). The market includes consumer services (television, radio, and broadband) and mobile services (data and voice). Satellite TV services represent about 75% of all revenues in the space sector, and further growth is anticipated in this sector through emerging markets, additional high definition channels, and the introduction of ultra high definition services.

To allow a single communications satellite (comsat) to address several different markets simultaneously, a small number (typically 3–4) of customized antennas are employed, as illustrated in Figure 7. The amount of information received and transmitted by a comsat, that represents its overall ability to generate revenue, is directly proportional to the total area of its antennas. As illustrated in Figure 8, doubling the antenna diameter from 30 cm to 60 cm leads to an increase in area of a factor of 4, and delivers an increase in the gain of the signal of 5.4 decibels-isotropic (dBi), which corresponds to an increase in signal strength by a factor of about 3.5.[1] Communications satellites are therefore designed to maximize the total antenna area that can be accommodated within the fairing of a single launch vehicle.

Source: http://space.skyrocket.de/img_sat/telstar-567__1.jpg.

Figure 7. Example of a Communications Satellite Showing Three Antennas Customized for Specific Markets Defined by Their Geographic Location



Antenna Size & Performance Comparison

Gain	Diameter (r x 2)	Surface (π x r²)	Increase
48.0 dBi	240 cm	45239 cm²	+156%
43.9 dBi	150 cm	17671 cm²	+56%
42.3 dBi	120 cm	11310 cm²	+44%
40.0 dBi	100 cm	7854 cm²	+178%
35.7 dBi	60 cm	2827 cm²	+300%
30.3 dBi	30 cm	707 cm²	

calculated at 12.5GHz, 70% efficiency

Source: Satmarin (2017).

Figure 8. Relationship between Performance and Antenna Size

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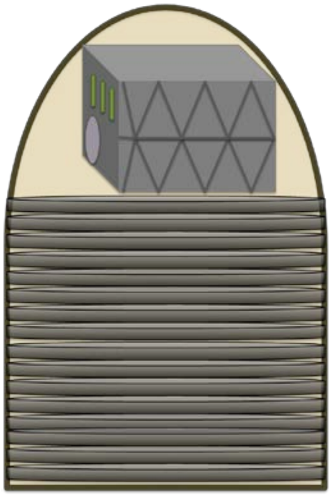
[1] Decibels-isotropic (dBi), the unit of measure for antenna gain, is usually defined as the ratio of the power transmitted in the direction of peak radiation to that of an isotropic source. (Antenna Theory 2017).

On-orbit assembly offers the potential opportunity to significantly enhance comsat performance by breaking the limitations imposed by launch vehicle fairing size. Two possible approaches could be pursued for increasing the total antenna area. First, to increase the total number of antennas that can be deployed into orbit, the antennas could be stowed into the launch vehicle with greater geometric efficiency by assembling them on orbit using robotic assembly techniques. An illustration of the proposed packing approach is shown in Figure 9. Once the platform and antennas have been delivered to orbit, assembly enabled by advances in robotics and autonomy would be performed to deploy the antennas on to the satellite. This approach benefits from modularity and increases total throughput, thereby providing increased revenue to the operator.

Alternatively, the ability to deploy the same number of antennas, but where each is of larger size than can be currently launched, would also increase the throughput of each spacecraft, again providing increased revenue. This approach may provide additional benefits as a larger antenna allows the beam to be more effectively focused, thereby reducing power losses. Depending on the particular communications market being addressed, increased on-orbit power generation may also be a requirement for either of these on-orbit approaches to increasing total transmission throughput. The electrical power consumed by the communications payload is proportional to total throughput, and, to a good approximation, the total required area of the solar arrays is proportional to the total area of all transmission antennas. On-orbit assembly would therefore also be needed to provide larger solar arrays than can currently be launched and deployed in a single vehicle.



Sources: SSL (2015) at left; STPI illustration at right.

Notes: Antennas deployed on a communications satellite prior to launch (left) must be folded up for integration into the launch fairing, and then un-folded again in orbit, which limits the number of antennas deployed. A more efficient packing concept (right) allows for the launch of a larger number of antennas that are subsequently assembled onto the communications platform once it is on orbit.

Figure 9. Actual and Notional Satellite Deployment Concepts

The following case studies illustrate the revenue return to be gained from on-orbit manufacturing and assembly for space-based communication missions.

Case Study: Increased Utilization of a GEO Comsat

Consider the data distribution sector where the comsat is used to move data from one central location to focus on other regions of the world. A typical comsat has four antennas that allow it to distribute data to four different regions simultaneously. Due to the dynamic nature of end-user data distribution requests, these comsat systems typically achieve utilization rates of only 60 to 70% (personal communication with Rob Schwarz of Space Systems Loral, November 2016). An increase in the number of antennas, without changing any other part of the satellite, would enable an increase in total utilization. For the purposes of illustration, we assume that increasing the number of antennas from three to six would increase the utilization efficiency by 10%. The antennas are not assembled onto the spacecraft prior to launch, but rather are packed efficiently into the fairing above the satellite platform. Once in orbit, the antennas are assembled robotically onto the satellite before transfer to GEO.

Assuming the satellite generates revenue at a rate of $1.5 million per transponder per year (the recent historical average), a typical number of 36 transponders on the comsat, and a 10% increase in utilization due to the use of on-orbit assembly to double the number of antennas from three to six, the total increase in revenue would be $5.4 million per year. Over the 15-year lifetime of a typical comsat, this yields a total revenue increase of $81 million, which is about half the value of a typical comsat, not including launch costs.

Another important limitation of communications satellites fully assembled on the ground is that once deployed on orbit, the technological capabilities remain fixed for the lifetime of the spacecraft. This is an important consideration since the lifetime of most GEO satellites is 15 years. The ability to reconfigure a telecommunications satellite through on-orbit re-assembly could provide valuable capability upgrades for operators. For example, a larger number of low-power payloads could be installed to address emerging smaller markets in place of a small number of high-power payloads for large markets. Alternatively, the beam distribution could be altered by re-arranging the transponders.

Case Study: Technology Refresh of a GEO Comsat

The revenue generated by a communications satellite depends primarily on the rate at which information can be moved through the system, measured in bits per second. Like Moore's Law for computer processor speed, the historical data for the evolution of comsat bit-rate shows a predictable upward trend with no end in sight. Specifically, the bit-rate has been seen to increase by a factor of 10 every 7 years or so. When a new comsat is launched, in its first year of operation it provides the fastest bit-rate available in the market. However, each year that passes sees new comsats placed into orbit that exceed the performance of the older comsat. Thus, a 7-year old comsat is operating at a bit-rate that is a factor of 10 slower than the newest satellites in operation. Going forward, as GEO comsats begin competing with LEO-based comsats that may have refresh rates of 3–5 years or less, operating with outdated technology is likely to directly hit the bottom line of many comsat operators.[2]

Consider a new paradigm in which modular satellite design and on-orbit assembly make it possible to replace the entire communications payload on the comsat after 7 years of operation. The new payload would refresh the technology and instantly increase the bit-rate of the asset. As an illustration, assume the satellite generates revenue at a rate of $1.5 million per transponder per year (the recent historical average), and a typical number of 36 transponders on the comsat. We will further assume a factor of 10 increase in bit rate enabled by on-orbit assembly of the updated communications payload. However, this improved performance would be accompanied by a reduction in customer charge rate, and we assume for our analysis that the per-bit charge rate decreases by a factor of 5. The cost of the second launch is assumed to be $40 million and that of the new communications payload is estimated at $100 million. Figure 10 shows the accumulation of revenue over the operational lifetime of the comsat under the current paradigm and for the new approach in which the technology is refreshed after 7 years. The total revenue increase at end of life enabled by on-orbit assembly is about $300 million per satellite. It is clear that there is strong potential for significant gains in revenue through this application of on-orbit assembly.

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[2] SpaceX plans to deploy over 4,000 LEO satellites and be operational by 2021. OneWeb is expected to deploy over 650 LEO satellites and also be operational by 2021.

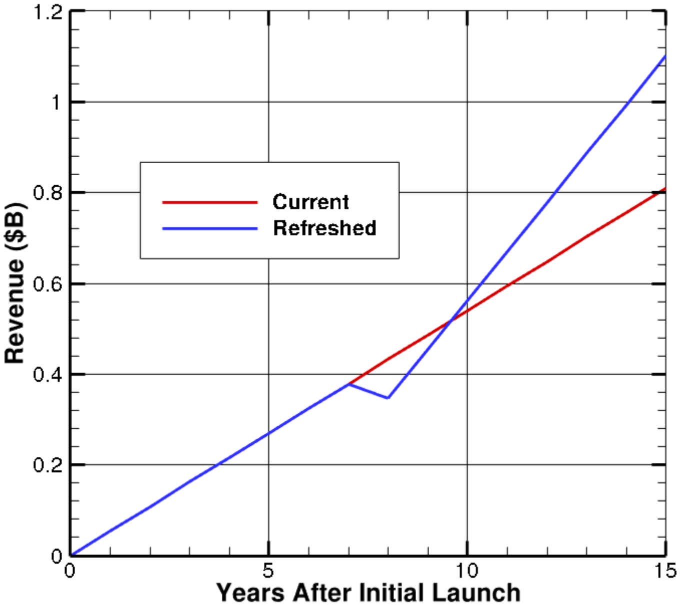
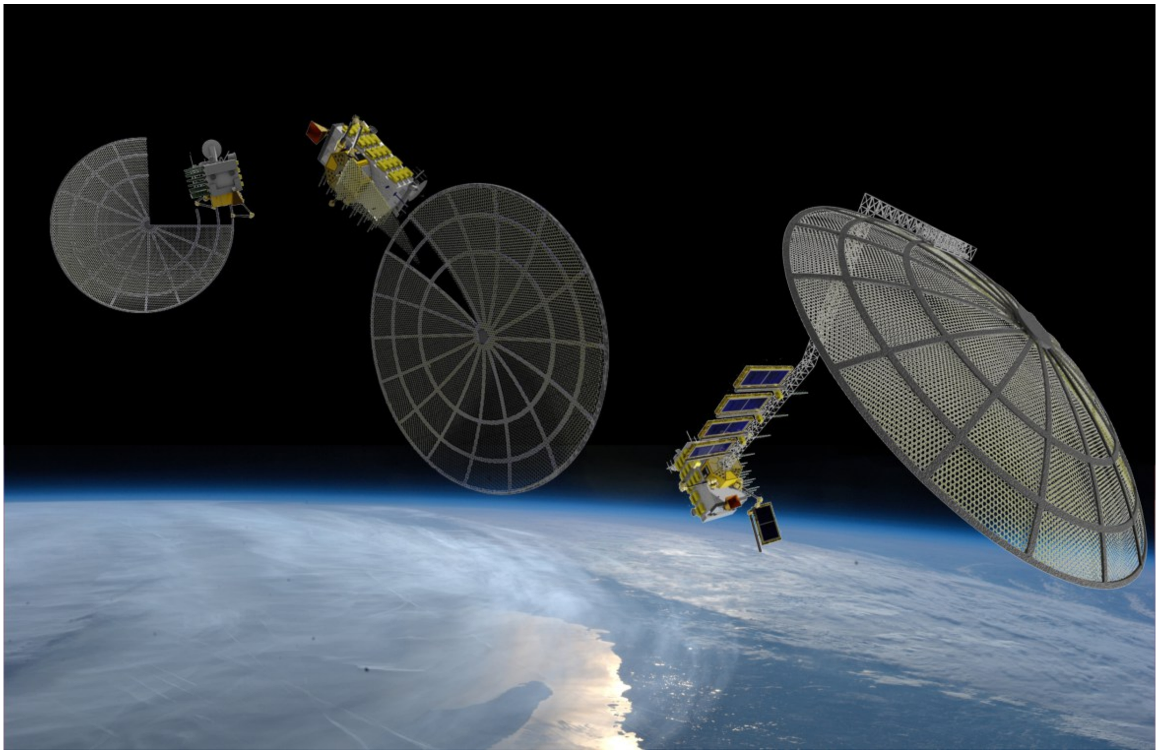


Figure 10. Total Revenue Generated by a Communications Satellite over a 15-Year Lifetime

While the previous case study considered GEO communications, this case study indicates that there is also significant current activity in the development and operation of large LEO constellations for telecommunications applications such as broadband internet (e.g., OneWeb) and data services (e.g., OrbComm). For the larger constellations consisting of several hundred to thousands of satellites, as illustrated in Figure 11, an ability to deploy an on-orbit factory to manufacture or assemble key components such as antennas may offer significant launch savings by benefiting from economies of scale.



Source: Make In Space (2016a).

Figure 11. Concept for Manufacture and Assembly of Antennas On Orbit

D. National Security

The Department of Defense (DOD) employs spacecraft for a number of missions related to national security, including communications; intelligence, surveillance and reconnaissance (ISR); missile warning (MW); and battle damage assessment (BDA).

For military communications, one of the key challenges is being able to provide sufficient bandwidth to dispersed ground personnel in the highly dynamic environment of an extended campaign. On-orbit assembly of modular payloads onto persistent platforms may enable accelerated responsiveness by military comsats to meet evolving needs.

In terms of the imaging aspects of ISR, MW, and BDA, in many cases the spatial resolution and signal strength requirements are significantly more demanding than for civilian Earth observations. All of the potential benefits of on-orbit assembly discussed previously for astrophysics and astronomy applications of optical imaging also apply to DOD missions. For collection of radio frequency signals, extremely large antennas, with linear dimensions on the order of hundreds to thousands of meters, would provide unprecedented levels of resolution. Such large structures cannot be accommodated within current launch vehicles, but could be constructed in space through a combination of on-orbit manufacturing and assembly.

The national security mission involves an ever-changing geopolitical landscape. Another important limitation of the current approach for fielding spacecraft is that it does not provide sufficient flexibility with respect to changing missions after a satellite is launched into orbit. For example, the desire to detect a new type of signature emanating from an area of the world already covered by U.S. satellites would require the deployment of a new satellite. On-orbit assembly approaches that enable modular payloads to be switched in and out of a cooperative platform, including technology upgrades and entirely new functionality, could provide significant benefits to military missions in terms of increased responsiveness to new threats and opportunities.

A third limitation of the current approach to military spacecraft is their vulnerability to attack. Most military spacecraft are not hardened to any significant extent against hostile actions, and they have only limited information on their immediate environment. The desire for increased resilience, defined as the ability to operate at some level during an attack and emerge with residual capability, could be increased significantly through on-orbit assembly. For example, the ability to install or assemble new space situational awareness sensors onto already orbiting assets would increase a spacecraft's understanding of its environment. On-orbit assembly could also enable newly developed defensive measures to be deployed and upgraded during the operational lifetime of a military satellite.

E. All Missions

Terrestrial construction of any spacecraft requires all of its components to undergo ruggedization to withstand the harsh launch environment that includes severe vibrations, acoustics, acceleration loads, and thermal loads. Such hardening processes impose significant penalties in terms of mass and size that ultimately limit payload capabilities and increase launch costs. For example, on a communications satellite, about 12% of the total dry mass of the spacecraft is required to stiffen structures to survive launch (Schwarz, personal communication). For a representative communications satellite mass of 6,700 kg, and a launch cost to GEO of $18,000 per kg,[3] eliminating such penalties through orbital manufacturing and assembly procedures would result in a cost saving of about $14 million.

In addition, extensive pre-launch testing of the hardened components is not only expensive but can also represent as much as 3% of the overall spacecraft development schedule of a communications satellite, about 3 to 4 weeks (Schwarz 2016). While substantial effort is expended in hardening and testing spacecraft components to survive launch, the savings that orbital manufacturing and assembly approaches could yield are

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[3] Derived by using launch costs advertised by SpaceX for the Falcon-9 launcher to geostationary transfer orbit (GTO), and assuming that for every 10 kg launched to GTO, only 6 kg makes it to GEO due to the extra propellant needed. Source: SpaceX "Capabilities & Services," http://www.spacex.com/about/capabilities.

relatively modest in comparison to some of the mission-specific benefits discussed previously in this chapter.

F. Mission Areas Where Payoff is Significant

Spacecraft are employed for different applications; the potential benefits from on-orbit manufacturing and assembly vary across these missions from minimal to significant value added. Figures 12 and 13 illustrate how the application of on-orbit manufacturing and assembly could alleviate the limitations shown in Figures 1 and 2 that are imposed by the current approaches to deploying spacecraft. Specifically, for space science missions, Figure 12 shows how assembling several payloads onto a persistent platform, assembling a large space telescope over several launches, and conducting on-orbit manufacture and assembly to eliminate the stresses of launch, all contribute to enhanced science return and cost reduction. Similarly, for communications satellites, Figure 13 shows how assembling more antennas onto a single platform, conducting on-orbit manufacture and assembly to eliminate the stresses of launch, and assembling refreshed payloads onto an existing platform, all contribute to increased system performance and revenue return.

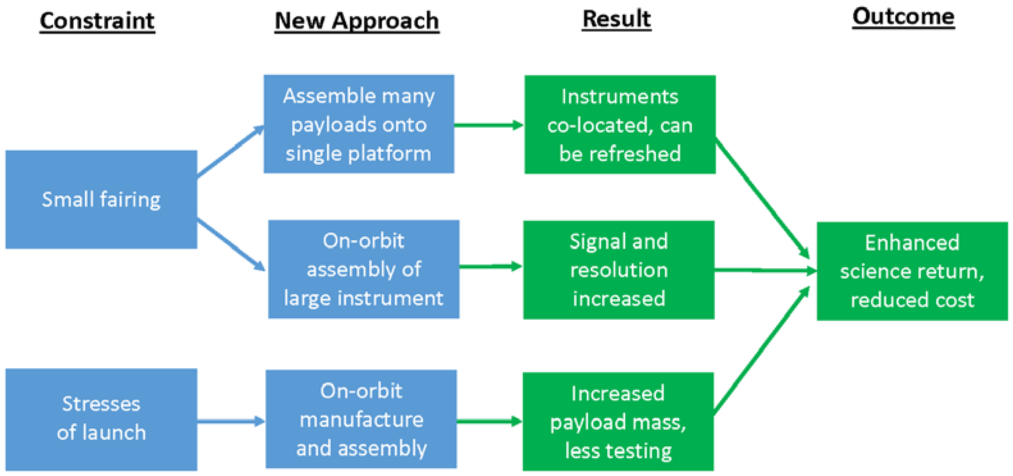


Figure 12. How On-Orbit Manufacturing and Assembly Approaches Could Alleviate Limitations Associated with Current Approach to Deploying Space Instruments to Enhance Science Return and Reduce Cost

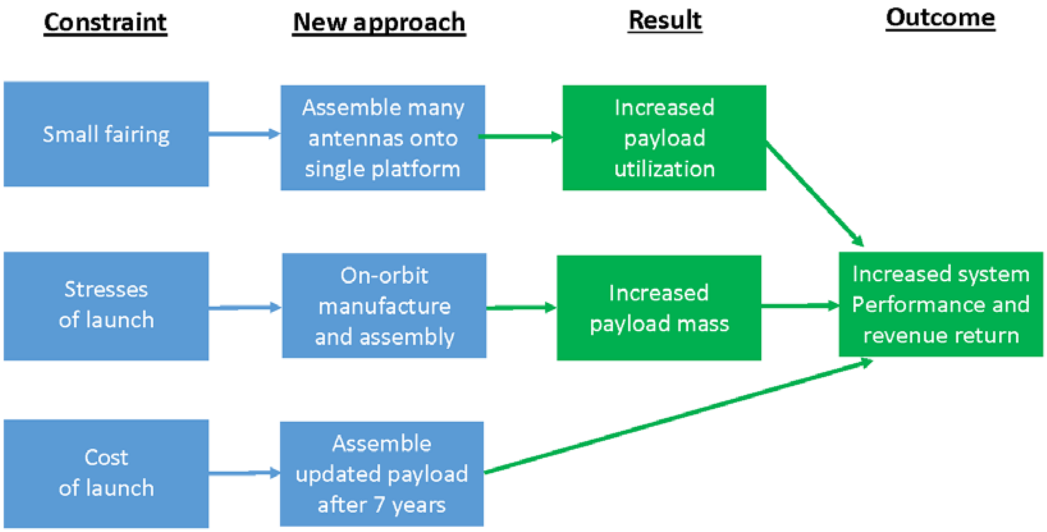


Figure 13. How On-Orbit Manufacturing and Assembly Approaches Could Alleviate Limitations Associated with Current Approaches to Deploying Communications Satellites to Enhance System Performance and Increase Revenue Return

Table 1 provides a summary of the spacecraft missions in which payoffs from orbital manufacturing and assembly approaches are potentially most significant. The quality and quantity of space science data that could be collected are improved. Space exploration is enhanced through increased flexibility and by the ability to build larger spacecraft than can be launched from the Earth. For communications satellites, on-orbit assembly could increase asset utilization and allow for periodic refresh of the payloads. Each of these enhancements would increase system performance and generate additional revenue. Like space science missions, national security reconnaissance missions would benefit from the larger instrumentation that could be deployed through on-orbit assembly. In addition, the opportunity to add and replace payloads onto a compliant platform through on-orbit assembly offers the benefits of increased responsiveness and resilience.

Table 1. Spacecraft Mission Areas and Applications that Would Benefit the Most from Orbital Manufacturing and Assembly

Mission Area	Capability Offered	Scientific or Financial Payoff
Astrophysics and astronomy	Larger telescopes than feasible to build and launch terrestrially	Assembly of larger mirrors in space could increase the number of exoplanets discovered by factors of 3 to 9 and could provide statistically meaningful information Cost savings of billions of dollars can be achieved by evolving the large telescope over several launches.
Earth science	Assembly of multiple payloads onto one persistent platform	Assembly of multiple payloads onto one persistent platform could enable faster refresh of technology, more cost-effective weather and climate observations, and launch savings of more than $500 million
Space exploration	On demand tools and replacement parts	Manufacturing small components from raw feedstock could reduce the volume and mass of redundant spares that need to be carried and thus increase resilience, particularly for crewed missions
	Larger spacecraft than feasible to cost-effectively launch from Earth	Assembly of lunar and Mars exploration vehicles based on teleoperation, robotics, and autonomy could significantly reduce cost and risk to life of astronaut assembly and reduce dependence on Earth
Space-based communications satellites	Increased revenue, capabilities and flexibility of operations	Assembly of a refreshed payload after 7 years could increase revenue by several hundred million dollars Doubling the number of antennas deployed could increase revenue by about $80 million
National security	Increased capabilities and flexibility of operations	Assembly of larger apertures could achieve greater spatial resolution and improve ISR Assembly onto existing platforms of sensors for increased situational awareness, defensive measures to increase resilience, and updating payloads with increased or different capabilities

3. State of the Art in On-Orbit Manufacturing

A. Introduction

The history of on-orbit manufacturing dates back farther than might be expected. In 1969, aboard the Soyuz 6, cosmonauts used a welding unit called Vulcan to test welding techniques in space (NASA 2016c). Vulcan tested several different types of welding techniques in outer space conditions and used remote handling equipment. A few years later, aboard Skylab, astronauts conducted experiments involving welding techniques and how to process various alloys in microgravity. In the mid-1970s, NASA and what was then Grumman Aerospace built the Beam Builder which was meant to bend, weld, and assemble aluminum (NRC 2014b, 26). The aim was to construct beams that could be assembled into larger structures. In the 1990s, using a KC 135, NASA researchers tested computer-aided design tools and fused-deposition modeling devices using a Stratasy 3D printer (NRC 2014b, 29).

Today, on-orbit manufacturing captures a variety of potential techniques, including additive manufacturing (3D printing) and conventional manufacturing techniques such as welding or chemical processes. This report focuses in particular on additive manufacturing in space for space (e.g., antennas) versus general manufacturing in space. We also do not emphasize manufacturing in space for terrestrial use (e.g., exotic optical fiber or silicon carbide).

NASA and other stakeholders of the federal government are currently investing in or have invested in research on understanding and developing on-orbit manufacturing capabilities. Such capabilities include manufacturing components, creating sensors or entire satellites, and recycling components (Werkheiser 2014, Clinton 2016).

Manufacturing components would entail creating replacement components or new components for assembly. According to a report for the National Academy of Sciences, a significant number of hardware failures (over 28%) on the ISS are made of polymers that might be repaired using additive manufacturing technologies (NRC 2014b, 31). Thus, the ability to additively manufacture small polymer components could prevent the need to launch replacement parts. Additionally, for future missions where launching replacements is exorbitantly expensive (in other words, in a deep-space mission), these techniques could prove to be invaluable in unforeseen circumstances; additive manufacturing could be used to replace a broken or missing part or to make a completely new tool.

Larger structures like antennas, sensors, or entire spacecraft could also be manufactured on orbit, either as a single unit or it in multiple components where it would then be assembled autonomously or with the assistance of humans (NRC 2014b, 36). Producing such components would likely require the ability to use additive manufacturing with metal as the feedstock, a technology that has yet to be developed for space.

An on-orbit recycler is a concept that would repurpose spacecraft or satellite parts that are no longer in use. The recycled components could be used as feedstock to additively manufacture larger components such as antennas.

In summary, on-orbit manufacturing could be leveraged to transform architectures in several ways. On-orbit manufacturing could enable the use of larger, more complex, and more delicate structures in space. The ability to produce spare parts could prove beneficial to humans in space as well as robotic spacecraft in need of repair. The ability to create a recycling center could help reduce the amount of additional mass needed to develop new components.

B. Current Programs

Only a few programs currently exist to support the development of these and other on-orbit manufacturing techniques. In 2014, Made In Space launched a 3D printer to the ISS in partnership with NASA as a technology demonstration project. This was the first 3D printer in space. It used plastic (acrylonitrile butadiene styrene) as feedstock (Made In Space 2016a). Samples were returned to Earth to compare to terrestrially manufactured equivalents. The results showed that the terrestrial tools and space-manufactured tools were virtually equivalent in properties; in other words, microgravity had little effect on the manufacturing process. As a follow-on project, Made In Space launched the Additive Manufacturing Facility (AMF) to the ISS March 2016. The AMF is a permanent manufacturing facility that can use a variety of polymers, including acrylonitrile butadiene styrene green polyethylene, and a blend of polyetherimide and polycarbonate (Made In Space 2016b).

In addition to work on the ISS, some NASA centers, in collaboration with various partners are researching other advances in in-space manufacturing. For example, Ames Research Center and Marshall Space Flight Center (MSFC) in collaboration with the Jet Propulsion Laboratory (JPL) are developing capabilities to manufacture electronic and photonic components in space (Werkheiser 2014). Together, they have developed prototypes of flexible electronic systems, including resistors, antennas, capacitors, photoresistors, and thermistors. Researchers at the Johnson Space Center and the MSFC are looking at a process to repair damaged components in space. In particular, this team is looking at simulating fixing panels that have been damaged from micrometeoroids and orbital debris. The Kennedy Space Center and MSFC are working on a project with the Army’s Engineer Research Development Center on additive construction in space (Werkheiser 2014).

NASA is also funding Small Business Innovation Research (SBIR) contracts that look at on-orbit and in-space manufacturing. For example, Tethers Unlimited has the SBIR SpiderFab project, which looks at using compact materials to manufacture large structures in space like solar arrays and antennas (Tethers Unlimited 2016). This project involves a spider-like robot that uses spools of thread to form the trusses that make up these large structures. Firmamentum, a subsidiary of Tethers Unlimited, is also funded through NASA SBIR contracts to further expand space-based 3D printing capabilities (*Space Angels* 2017). Through multiple awards, Firmamentum has developed the Refabricator that prints plastic objects and reprocesses plastic objects back into feedstock. Other concepts include a Massachusetts Institute of Technology (MIT) fabrication laboratory, dubbed the *fab lab*, which features a variety of tools for in-space manufacturing, including a computer-controlled laser cutter, two milling machines, a sign cutter, and programming tools (MIT 2016).

It should be noted that there is a great deal of other research that has looked or is looking into terrestrial additive manufacturing for space uses and though these technologies are not necessarily intended to be used in space, they could lead to advancements in in-space manufacturing. In particular, research at NASA Langley Research Center is looking at using additive manufacturing involving alloys, a technology that could be transferable to on-orbit manufacturing, which could enable the use of a wider range of materials and production of new structures.

Looking toward the future, NASA has plans in the coming years to conduct technology demonstrations for four types of manufacturing techniques in space: a recycler, printable electronics, synthetic biology, and metals manufacturing (Werkheiser 2014, Clinton 2016). Additionally, there are plans for developing an integrated facility system to look at materials like polymers and metals. Further down the line (10 years and beyond), NASA aims to develop the ability to use in situ materials for manufacturing and feedstock. Future goals include advancing additive manufacturing technology so that several types of materials can be used. For example, most communication satellite antennas are made of metal, so in order to manufacture antennas on orbit, in-space additive manufacturing technologies would need to advance to using metals as feedstock. While no such technology for in-space manufacturing currently exists, terrestrial 3D printers that use metals have been developed and could be leveraged.

In terms of potential for combining additive manufacturing with in situ resource utilization, Balla et al. (2011) describe some early progress where small parts were fabricated and characterized through use of lunar regolith simulant as feedstock in a laser-based additive manufacturing approach. Figure 14 shows a small propulsion assembly that was additively manufactured from metallic asteroid material (Planetary Resources 2016). The asteroid was melted under high vacuum and then atomized to create the powder feedstock.

Source: Planetary Resources (2016).

Figure 14. Spacecraft Propulsion Structure 3D Printed from Actual Asteroid Material

While the United States has taken the lead in on-orbit manufacturing, ESA is also investing in this area. The Additive Manufacturing Aiming Towards Zero Waste and Efficient Production of High-Tech Metal Products (AMAZE) project aims to develop space-quality metal-based components created through additive manufacturing, both on the ground and on-orbit (ESA 2013). A 3D printer using metal powder that is designed for use in space has been developed in the United Kingdom (*The Times* 2016), tested in the freefall, weightless environment created by a diving airplane, but has not yet been operated on-orbit. More recently, ESA formed a consortium with four European companies to develop an additive manufacturing capability for on-orbit use on the ISS (All About 3D Printing [All3DP] 2016). The project is called Manufacturing of Experimental Layer Technology (MELT) and aims to design, develop, and test a fully functional 3D printer that can fabricate structures using polymers with acceptable mechanical and thermal properties while functioning under the microgravity conditions of the ISS. The project is scheduled to deliver hardware in May 2017.

C. Technical Challenges

Several challenges remain before the full potential of on-orbit manufacturing can be realized. There may be some limitations to the types of items that can be manufactured in space. Such limitations could be caused by a variety of factors, including the component material(s) required for a particular structure, the size of the object to be manufactured, the amount of time required to execute the architecture, the configuration of the object being manufactured, and the power needed to support the manufacturing process. For example, the current 3D printer on the ISS has only used polymer as feedstock. Many essential spacecraft components are made of other materials, including metals and composites. Metal structures could be made through a number of different additive manufacturing approaches such as laser sintering. Terrestrial approaches for manufacturing of fiber reinforced polymer composites are well developed, but may face unique challenges in the zero-gravity orbital environment. It is also important to recognize that many functional structures involving highly complex mixtures of materials, such as cables and computer chips, may not be manufactured on orbit for several decades.

While there are a number of manufacturing processes that could be deployed on-orbit, so far only additive manufacturing on the ISS has been demonstrated, and even then only on a small scale. The AMF 3D printer on the ISS has a print volume of 14 cm × 10 cm × 10 cm. Clearly, many critical spacecraft components such as antennas are significantly larger. A small ratchet took four hours to manufacture on the first 3D printer installed on the ISS. By extrapolation, larger components will require days and even weeks of continuous manufacturing. The AMF printer consumes 600 watts (W) of energy, which is relatively small. However, the need to scale-up and accelerate manufacturing would increase power consumption significantly. In addition, the power required for manufacturing metal structures would be significantly larger. For example, direct metal laser sintering was found to consume power at a rate that is more than a factor of 10 higher than an additive manufacturing process for polymers (Mognol, Lepicart, and Perry 2006).

Another important challenge facing on-orbit manufacturing is achieving the required precision demanded by geometrically complex structures such as antennas and precision instruments. For example, antennas need to be very smooth, and ensuring that is the case requires on-orbit implementation of high-accuracy metrology techniques.

Many on-orbit assembly capabilities are challenged by the space environment: lack of significant gravitational acceleration, presence of atomic oxygen, exposure to radiation, and impacts from micrometeorites and orbital debris. For LEO operations, there are also continual variations in the thermal environment caused by going in and out of eclipse. These variations may negatively impact manufacturing processes. Additionally, support infrastructure would need to be implemented to make space-based manufacturing facilities possible. It may therefore be necessary to deploy a protective shell structure in orbit, essentially representing a factory, in which manufacturing can proceed free from many of these environmental concerns.

As is the case with terrestrial processes, characterization and verification of the manufactured product would be required. Such characterization was a key element of the 3D printing experiments on the ISS. The objects printed on-orbit underwent a number of tests after return to the Earth. The measurements revealed minimal differences in material properties from identical components printed on the ground (Prater et al. 2016). Clearly, the future implementation of on-orbit manufacturing would require in situ, non-destructive evaluation of the manufactured structures. In instances where humans would not be present to perform these verification tests, automation would need to be further developed (NRC 2014b).

As a result of the various technical challenges, the private sector may be averse to risks associated in investing early in on-orbit manufacturing technologies that may not be brought into fruition or may not have a business cases for several years down the line. As such, government participation may be needed to further advance in-space manufacturing technologies (NRC 2014b).

D. Summary

In this chapter, we discussed the current approaches and challenges to on-orbit manufacturing of tools, replacement parts, and spacecraft components such as antennas. Additive manufacturing of small components made of polymer feedstock has already been demonstrated on ISS. NASA and ESA are working on other approaches to manufacturing structures made from other materials, including metals and composites, but success appears to be at least 5 years away. No larger-scale manufacturing capabilities have been demonstrated on orbit. Therefore, the manufacture of large structures or structures with more complex material compositions, like solar arrays, are farther down the line. Issues associated with process verification and development of manufacturing standards can be expected to benefit from progress being made in terrestrial manufacturing activities.

4. State of the Art in On-Orbit Assembly

A. Introduction

The on-orbit assembly of spacecraft as described in this analysis would ultimately be conducted without astronauts present, and would require development of a number of technologies and processes involving sensing, robotics, and automation. Relevant space activities that represent intermediate steps to full on-orbit assembly include on-orbit inspection and servicing of spacecraft. A significant heritage has been built up over the last 50 years in astronauts conducting on-orbit inspection, servicing, and assembly. Lessons learned from all of these activities will inform future missions and new techniques. Due to the long history of human-assisted on-orbit inspection, servicing, and assembly, as well as current projects that are based on robotic approaches, significant impact from on-orbit assembly is likely to occur in a nearer time frame than on-orbit manufacturing.

The methods and goals of human-assisted on-orbit inspection are illustrated by Space Shuttle *Discovery*'s flight STS-114, the first return to flight after the Space Shuttle *Columbia* disaster. During this 2005 flight, astronauts used the Orbiter Boom Sensor System (OBSS) to inspect *Discovery*'s wings and nose cone. The OBSS had been developed in the wake of the *Columbia* disaster to help identify potential faults in the Shuttle's thermal lining. The entire survey of the wing and nose cone took about 7 hours. Engineers on the ground reviewed the photos and data in real time to identify areas requiring further inspection (NASA 2005a). When two protruding gap fillers between thermal tiles were identified, astronaut Stephen Robinson removed the gap fillers by hand. This sort of spacewalk repair was unprecedented and ensured the safety of *Discovery* for the remainder of its mission (NASA 2005b).

Capabilities are being developed for automated inspection of on-orbit spacecraft. For example, the Air Force Research Laboratory (AFRL) Automated Navigation and Guidance Experiment for Local Space (ANGELS) spacecraft investigated technologies and procedures for maneuvering and imaging within a few kilometers of an expended rocket body (AFRL 2014). Concepts are also being developed using sensors for inspection of spacecraft. For example, the MIT Integrated Navigation Sensor Platform for Extra-Vehicular Activity (EVA) Control and Testing (INSPECT) concept is comprised of a sensor suite hosted on a free-flying platform and is intended for testing on the ISS to reduce the need for astronaut EVA (Sternberg 2015).

The first instance of on-orbit servicing occurred in 1973 when Skylab was launched and its micrometeroid shield and solar arrays failed to deploy. This resulted in various thermal management problems and the first crewed mission to Skylab replaced the thermal shield (NASA GSFC 2010). Another early example of on-orbit servicing includes the Solar Maximum Mission (NASA GSFC 2010). The attitude control system of the Solar Maximum Mission probe failed in 1981 and was repaired by the Challenger crew in 1984. The spacecraft was well modularized and it would have been relatively simple to repair on the ground or in orbit, pointing to the benefits of modularity for on-orbit servicing and assembly.

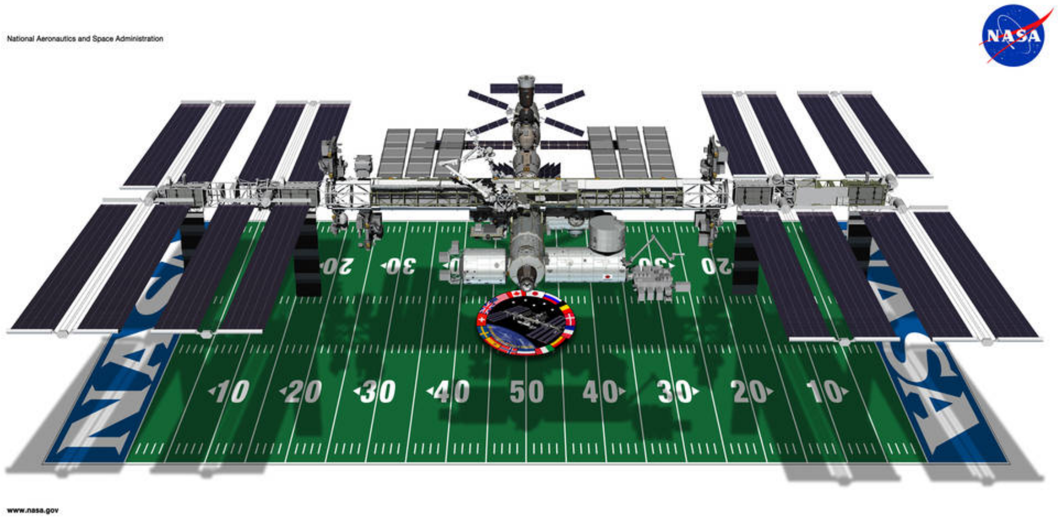
The Hubble Space Telescope (HST), launched in 1990, was built with on-orbit servicing in mind (NASA GSFC 2010). Astronauts were trained in the intricacies of the systems and the modularity of the parts. After launch, a servicing mission ensued to repair the mirror and blurry optics. Five servicing missions over the next 12 years followed, lengthening the lifespan of the telescope and improving its capabilities. HST still produces valuable science today.

Partly motivated by the frequent Hubble servicing mission and partly motivated by the Columbia accident, Northrop Grumman designed a Hubble Robotic Servicing Vehicle (Lillie 2006), complete with two robotic arms having seven degrees of freedom and a 23-foot total armspan called Dextre developed by Macdonald, Dettweiler, and Associates (MDA) of Canada. This vehicle could have completed the tasks associated with the fourth Hubble servicing mission, which involved replacement and upgrades of scientific instruments, either autonomously or teleoperatively.

MDA has extensive experience in robotic, human-in-the-loop servicing, having developed Canadarm for the Space Shuttle and Canadarm2 and Dextre for the International Space Station. These robotic arms assisted in the many EVAs required to service the ISS. They are also capable of servicing functions with astronaut supervision but without an extra-vehicular activity (MDA 2016). In 2013, robotic refueling was successfully demonstrated on the ISS using Dextre (NASA GSFC 2016). MDA is contracted to build robotic arms for the NASA Restore-L mission and the Defense Advanced Research Projects Agency (DARPA) Robotic Servicing of Geosynchronous Satellites (RSGS) missions (MDA 2016).

Autonomous docking and servicing was demonstrated by DARPA's Orbital Express in 2007 (DARPA 2007). The mission involved a surrogate next-generation satellite and a prototype servicing spacecraft. The satellites docked several times, and the prototype servicer refueled the satellite and exchanged modules.

The most famous example to date of on-orbit assembly is the construction of the ISS. As mentioned previously, the assembly of the station involved over 160 spacewalks spanning 1,061 hours (NASA 2016d, e). With assembly now complete, the station is the size of a football field as illustrated in Figure 15. The ISS encompasses over 900 cubic meters of pressurized volume and has been home to over 200 people representing 15 countries (NASA GSFC 2010).



Source: NASA (2017).

Figure 15. Size of the ISS Compared to a Football Field

B. Human-Assisted Assembly and Servicing

Human-assisted assembly will continue to play an important role in on-orbit assembly, be it with manual or teleoperative construction. Human activities on orbit are costly and pose a risk to human life, illustrating the benefit of human-in-the-loop on-orbit activities. A spectrum of robotic techniques could be used to supplement human assembly and servicing, from robots as eyes, subordinates, and sidekicks to robots as surrogates and specialists (NASA GSFC 2010).

The NASA Restore-L on-orbit servicing mission is scheduled for 2020 under the purview of NASA's Space Technology Mission Directorate, and it involves the refueling of LandSat-7. A service vehicle developed by SSL will autonomously rendezvous with the LandSat spacecraft and then tele-robotically cut wires, remove caps, and refuel the satellite. LandSat-7, an unprepared client built long before on-orbit servicing technology was available, will be about 20 years old at that point. MDA is contracted to build the robotic arm for this mission (MDA 2016.) Restore-L demonstrates the potential for robotic servicing to increase the lifespan and safety of current missions. Orbital ATK's Mission Extension Vehicle (MEV) is another example of a servicing capability that is under development. The MEV is capable of docking with almost any GEO communications satellite. Once docked, the comsat can be moved to a different orbit, and/or conduct life extension servicing. In the future, client satellites may be designed and prepared for on-orbit refueling and the process may become routine.

The German space agency, Deutsches Zentrum fur Luft und Raumfahrt (DLR), is also interested in sustaining the operational lifetimes of on-orbit assets. The Space Dynamics Department of Germany's Institute of Robotics and Mechatronics runs a mission called Deutsche Orbitale Servicing (DEOS) (Lal et al. 2015). DEOS involves two satellites, a *client* and a *servicer* (Krebs 2016). Planned to launch in 2018, the servicer will chase and rendezvous with the client, demonstrate refueling and module exchange, and then safely de-orbit the client (Krebs 2016, Albu-Schaffer 2013). DLR is also developing "light weight robots and hands for space application" which consume little energy and are extremely human-like in their agility and maneuverability (Albu-Scaffer 2013).

For many of the same motivating factors, DARPA is developing robotic servicing vehicles for GEO satellites as part of its RSGS project (DARPA 2016a). Satellites in this high orbit will be able to be repaired and maintained over time, increasing their capabilities and their value to their owners. This project began in 2016 and the planned launch date is 2021 (*Military Aerospace Electronics* 2016). The robotic arm will be built by MDA (MDA 2016).

In early 2016, ESA flew the Intermediate Experimental Vehicle (IXV); in 2020, it is expected to fly Program for a Reusable In-orbit Demonstrator from Europe (PRIDE) (British Broadcasting Corporation [BBC] 2015). IXV demonstrated many key capabilities for on-orbit maneuverability; PRIDE will provide a platform for the experimentation with and development of on-orbit servicing capabilities (ESA 2015).

C. Self-Assembly

Self-assembly involves small satellites with specialized capabilities self-organizing to fulfill the objectives of a larger mission. Self-assembly is enabled by advances in formation flight.

Autonomous Assembly of a Reconfigurable Space Telescope (AAReST) is a mission developed by California Institute of Technology/JPL and Surrey Satellite Technology Ltd. that is scheduled for launch in 2018. AAReST aims to demonstrate the technology needed for telescope elements to position and attach themselves on orbit. The system comprises mirror segments and a cluster of CubeSats that can undock and navigate autonomously (Underwood et al. 2015).

DARPA is pursuing the satlet architecture concept for the Phoenix project, whereby small autonomous modules incorporate key satellite capabilities and aggregate in various combinations to achieve different mission goals. The modularity of the satlets increases mission resilience and re-configurability, reduces spacecraft design and integration time, and provides cheaper redundancies. In tandem with the Payload Orbital Delivery system, deployment costs are reduced (DARPA 2016b). Satlets have been under development since 2012, and the first LEO flight is planned for 2017 (Melroy et al. 2015).

D. Robotic Assembly

Payloads, subsystems, and vehicle modules could also be assembled in space by robots. One example, space telescopes, is discussed at length in Chapter 2. In 2015, Orbital ATK in partnership with NASA Langley Research Center was granted a NASA Tipping Point award to demonstrate the Tendon-Actuated Lightweight In-Space Manipulator, or TALISMAN, on the ground (NASA 2015a). TALISMAN will increase capabilities "to extend reach, reduce mass, apply force, and package efficiently" (NASA 2015b). Another Tipping Point award was given to Space Systems Loral's Dragonfly project. The project plans to demonstrate high-fidelity robotic assembly of antennae on the ground (NASA 2015a). The goal is to eventually be able to completely assemble satellites on orbit having larger and reconfigurable apertures and higher performances than satellites that are currently launched (NASA 2015a, *Satellite Today* 2015). In addition, the capabilities that will be demonstrated in NASA's Restore-L mission are clearly applicable.

E. Combining On-Orbit Manufacturing and Assembly

Having separately considered the status of on-orbit manufacturing and on-orbit assembly, we consider the situation for the combination of these two processes.

One such construction concept is Made In Space's Archinaut that received a NASA Tipping Point award in 2015 (NASA 2015a). Archinaut consists of robotic arms used for manipulation and assembly of the structures produced by an associated additive manufacturing machine capable of processing relevant materials (NASA 2015a). For this project, Made In Space has subcontracted Northrop Grumman for the systems engineering and with Oceaneering Space Systems of Oceaneering International for the manipulator arm (*SpaceNews* 2016a). The final version of Archinaut will have three arms. An on-orbit demonstration is expected in 2018 (*SpaceNews* 2016a). Archinaut will enable the construction of large antennae for spacecraft on-orbit as well as augmentation and repurposing of existing spacecraft (Made In Space 2016a). An added benefit of this system is the ability to gather and recycle orbital debris (*SpaceNews* 2016a).

Another concept for on-orbit manufacturing and assembly is Tethers Unlimited's SpiderFab. A technology demonstration is planned for 2020 with support from a NASA Innovative Advanced Concepts Grant (Hoyt 2013). SpiderFab is a *satellite chrysalis* containing raw material that is assembled into a space system, essentially a self-fabricating satellite. Such a system could be used to build trusses and lay solar panels or use many robotic arms to produce a supporting web structure for large antennae or starshades, which allow observation of faint objects by blocking light from bright objects (Hoyt 2013).

F. Technical Challenges

While on-orbit assembly may provide significant mission benefits, the development of such capabilities faces a number of technical problems. As previously noted, many on-orbit assembly capabilities are challenged by the space environment. It may therefore be necessary to deploy a protective shell structure in orbit, essentially representing a factory, in which assembly could proceed free from many of these environmental concerns. For LEO operations, there is also the continual significant variations in the lighting environment caused by going in and out of eclipse. These variations may negatively impact any vision-based alignment operations. Teleoperative missions are affected by communication latencies, particularly for deep-space missions such as those at the Moon and Mars, and therefore require tasks such as rendezvous and docking to be entirely automated. In addition to the cost of developing on-orbit assembly capabilities, spacecraft that are assembled on-orbit are costly even before launch and assembly (let alone validation) occurs. When not supervised by an astronaut, on-orbit assembly requires a robotic system with high reliability and a high degree of trust between human and robot. New procedures would have to be developed in order to verify that the assembly procedures have been executed as planned.

Some of the challenges faced by robotic, autonomous on-orbit assembly could be addressed by learning and benefiting from the much more extensive world-wide activities of terrestrial-based applications of the same technologies. Automated, robotic assembly of complex machines is widespread and their capabilities are increasing. Important examples include automotive and micro-electronics assembly in large industries as well as for assembly of components directly related to spacecraft, such as antennas and solar-cells.

G. Summary

The technologies and procedures required to facilitate on-orbit assembly are being actively pursued through several programs funded primarily by NASA and DARPA. Key themes for successful development include modular design of spacecraft, sensors, robotics, and autonomy. Progress being made in on-orbit inspection and servicing of spacecraft is laying the foundation for on-orbit assembly.

5. Roles for the U.S. Government

As discussed in Chapter 2, on-orbit manufacturing and assembly of spacecraft could add significant benefits to a number of space missions. Core technologies and procedures for orbital manufacturing and assembly are still in early development, and progress could likely be accelerated by appropriate actions from the federal government. In this chapter, we identify areas in which U.S. federal investments in research and development (R&D) could be expected to have the most impact. In addition, other steps that the federal government could take to facilitate and accelerate progress in orbital manufacturing and assembly procedures are described.

A. Summary of Current Efforts

1. National Aeronautics and Space Administration (NASA)

NASA is one of the two primary U.S. government agencies actively engaged in orbital manufacturing and assembly, both as a developer and as a funding source. The Additive Manufacturing Facility (AMF) currently operational on the ISS was funded by the In Space Manufacturing Initiative, which is managed by the NASA Marshall Space Flight Center (MSFC). The NASA Space Technology Mission Directorate (STMD) funds research on both on-orbit manufacturing and on-orbit assembly through mechanisms such as the Tipping Point program. There are also significant orbital manufacturing and assembly activities at Langley Research Center, Goddard Space Flight Center, and Jet Propulsion Laboratory.

To the best of our knowledge, the total spending on orbital manufacturing and assembly activities across NASA in fiscal year (FY) 2016 was about $18 million.

2. Defense Advanced Research Projects Agency (DARPA)

DARPA has also made significant investments in developing technologies that are key to orbital manufacturing and assembly. Under the Phoenix program, modular miniature satellites called satlets are being developed that can self-assemble on orbit to generate different spacecraft configurations. The Robotic Servicing of Geosynchronous Satellites (RSGS) project aims to increase satellite resilience through development of robotic capabilities for repairing and extending the lifetime of GEO spacecraft.

While DARPA spending for specific projects is not made public, the budget for the unclassified aspects of the RSGS project was $10 million in FY 2016, up from $4 million in FY 2015, and that of the Phoenix project was $19 million, down from $55 million in FY 2015, for a total of about $30 million (DARPA 2017).

3. Other Department of Defense (DOD) Organizations

The Air Force Research Laboratory (AFRL) has made minimal investments in orbital manufacturing and assembly activities. Other DOD organizations such as the National Reconnaissance Office (NRO) are investing in on-orbit assembly and manufacturing, but not much is publicly known about these efforts.

4. Private Sector

In the private sector, both large and small businesses are actively engaged in orbital manufacturing and assembly activities. Space Systems Loral (SSL) is developing the concept of a GEO-based Persistent Platform that would operate for 15–20 years during which time the revenue-generating payloads could be switched out using on-orbit assembly. Orbital ATK is developing its Mission Extension Vehicle (MEV) for servicing spacecraft that could pave the way for on-orbit assembly. This project involves a large internal investment of $100–200 million in the coming years.

For smaller/newer companies like Tethers Unlimited and Made In Space, most funding appears to come from the government rather than from private or internal sources. The 3D printers deployed on the ISS were developed by Made In Space using NASA funds. Made In Space also received a NASA Tipping Point award for the development of robotic arms for manipulation and assembly of structures produced by an associated additive manufacturing machine. Tethers Unlimited is funded by NASA to look at using compact materials to manufacture large structures in space like solar arrays and antennas.

Total commercial Independent Research and Development (IRAD) spending on orbital manufacturing and assembly activities in FY 2016 is estimated to be at least $10 million.

B. Gaps and Areas in Need of Funding

While some of the expected benefits of orbital manufacturing and assembly have strong connections to increased revenue and would be pursued in large part by the commercial sector, many others involve space science, exploration, and national security, which would require significant federal investment (currently under $50 million per year). Some of the key technical areas requiring such support are identified in the following subsections.

1. On-Orbit Manufacturing

On-orbit additive manufacturing has only been demonstrated so far using polymer feedstock to 3D print small objects such as tools, though efforts are underway to install a metal printer on the ISS (Werkheiser 2014, Clinton 2016). Spacecraft are composed of a wide range of structures manufactured from a number of different materials. While it is unlikely that all components of a spacecraft could be manufactured on orbit, there is a strong need to expand the range of structures that could be generated. Important types of materials for which on-orbit manufacturing processes must be developed include those for antennas, solar cells, trusses, and electronics. Another key area involves the development of technologies and procedures that would allow significant scale-up in the physical dimensions of structures that could be manufactured on orbit. The 3D printer on ISS has so far generated structures on the scale of 10–20 cm, whereas communications antennas are 1 m scale, trusses are 10 m scale, and radio-frequency apertures are 100 m scale. Clearly, significant progress is required to manufacture such structures.

Given the significant challenges that must first be overcome, we expect that it will be many years before on-orbit manufacturing would make a significant contribution to deployed space capabilities. First, additive manufacturing is a nascent field even for terrestrial applications. Many fundamental questions must be answered on issues such as structure-property relationships, standards, quality, and certification. Second, automated additive manufacturing capabilities on the ground are currently under development. A significant amount of further development would be required for automation of on-orbit additive manufacturing. Third, even on the ground, additive manufacturing techniques and processes require supporting infrastructure in order to be successful. For example, there is strong reliance on human oversight to assess the final product. Development of an on-orbit additive manufacturing capability must address the supporting infrastructure, including the extent to which humans are in the loop. For all of these reasons, it is highly unlikely that on-orbit manufacture of large components, let alone an entire spacecraft, will be possible for many years to come.

2. On-Orbit Assembly

As already noted, on-orbit assembly would benefit from progress being made in on-orbit inspection and servicing. These activities require many of the core technologies common to assembly, including sensing, robotics, autonomy, and teleoperation. In general, the steps associated with assembly would be more complicated than those for servicing, but development of modular spacecraft with cooperative interfaces would greatly reduce the complexity. On-orbit assembly presents new challenges beyond servicing, including the need for development of assembly processes for critical spacecraft structures such as antennas, solar arrays, and trusses. There is also a need to develop new sensors that could inspect the assembled spacecraft for verification of the construction process.

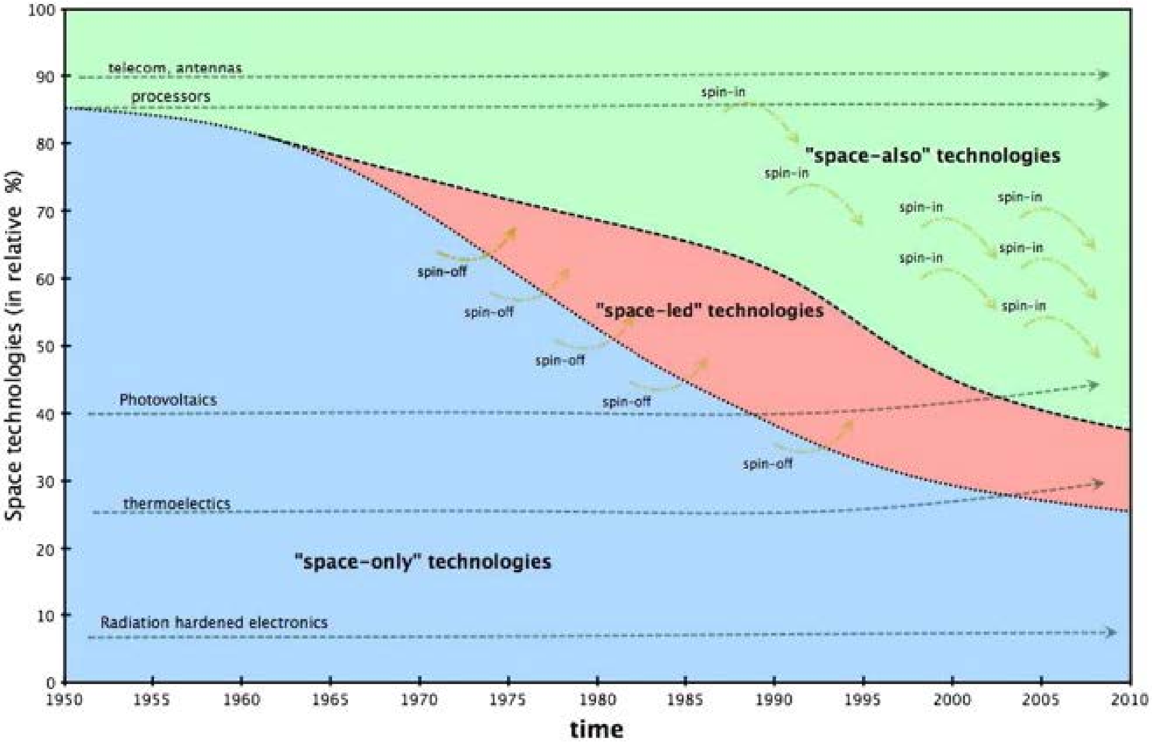
Due to the lack of accessibility of the orbital environment, there is a need for extensive spaceflight testing of procedures for both orbital manufacturing and orbital assembly before they would be accepted by space operators. The federal government could make a critical difference here by funding foundational on-orbit technology demonstrations. Important examples of recent and ongoing federally funded demonstrations relevant to orbital manufacturing and assembly include the 3D printer on ISS (NASA), the servicing mission Restore-L (NASA), and the servicing mission RSGS (DARPA).

3. Lack of Collaboration with the Terrestrial Sector

Our discussions with stakeholders revealed that, while there is communication and coordination across NASA, DARPA, and a handful of space companies, terrestrial firms do not seem to interact on topics focusing on additive manufacturing, robotics, or automation technology. This represents an important missed opportunity on the part of the space community.

At the beginning of the space age, few commercial off-the-shelf options were available, so most of the required technologies were newly developed (Lal 2015). The prevalence in the 1950s on specialized "space-only" technologies is shown in Figure 16 (lower portion in blue). In the 1960s, the technologies required for space missions became less specialized; some found applications in other fields. The emergence of these "space-led" technologies is shown in coral in the center portion of the figure. Of course, some technologies that were primarily developed for terrestrial uses have also found applications in space. These technologies that are spinning in to the space sector are labeled "space-also" technologies in the upper, green portion of Figure 16. These have clearly been increasing in number and are now dominating the other two technologies.

Many organizations are conducting state-of-the-art research in additive manufacturing, robotics and automation. For example: General Electric is investing $3.5 billion in additive manufacturing for aerospace applications (*Fortune* 2015); Toyota has invested $1 billion to create a research institute for artificial intelligence and robotics technology for automobiles (*IEEE Spectrum* 2015). The total US federal investment in robotics and intelligent systems is estimated at $220 million for FY2017 (Networking and Information Technology Research and Development 2017). None of the organizations with whom we spoke seem to be leveraging the terrestrial advances being made in these areas.



Source: Summerer (2012).

Figure 16. Growth of Technologies “Spinning In” from Outside the Space Sector

C. Facilitating Roles

The federal government could take several steps beyond direct funding of R&D to facilitate the development of orbital manufacturing and assembly operations.

1. Tools

Orbital manufacturing and assembly would involve some technologies and processes that apply to a wide range of activities. An important role that the government could assume is the development of tools, hardware, software, and procedures that apply to a range of orbital manufacturing and assembly approaches and that are made available to be shared with the entire U.S. space community.

2. Standards

The development of materials standards for terrestrial additive manufacturing processes is being performed in collaboration between the America Makes program (America Makes 2017) that receives significant federal support, and the private, non-profit American National Standards Institute (ANSI). While some of the standards developed in that activity will be directly relevant to space materials, the unique near-zero gravity environment will also require an entirely new set of protocols for on-orbit manufacturing.

DARPA has proposed the development of the Consortium For Execution of Rendezvous and Servicing Operations (CONFERS), a government-industry collaboration to establish technical and safety standards for on-orbit robotic activities required for repair and servicing of satellites (*SpaceNews* 2016b). The goal of CONFERS is to establish a forum that would use best practices from government and industry to develop non-binding, consensus-derived technical and safety standards for on-orbit servicing operations. In doing so, the program would seek to provide a clear technical basis for definitions and expectations of responsible on-orbit behavior. The ultimate goal is to provide the technical foundation to shape safe and responsible space operations to preserve a safe space environment for all. While many of the standards that may be developed by CONFERS for on-orbit servicing would be applicable to assembly, there would be unique aspects of assembly that require special consideration. For example, many of the potential benefits of on-orbit assembly involve the interchange of modular payloads on cooperative platforms. The development of standard interfaces would greatly facilitate the implementation of such approaches.

Both the America Makes/ANSI and DARPA/industry collaborations provide examples of private-public cooperation frameworks that could be applied for development of standards for on-orbit manufacturing and assembly of spacecraft. There are historical examples of other consortia—a well-known one being SEMATECH (Hof 2011)—where public private partnerships enabled technological leaps not feasible without the partnership.

3. Infrastructure

The government could support on-orbit manufacturing and assembly of spacecraft activities by providing access to infrastructure. For example, NASA could make astronauts and ground control personnel available to conduct and monitor activities to develop and test on-orbit manufacturing and assembly. Government-operated platform resources such as communications and power could be provided, for example by the ISS. It may also be possible for federal agencies to provide launch-share opportunities for delivery of raw materials for manufacturing and components for assembly.

4. Legal and Regulatory Issues

Overcoming the technology challenges is not enough to ensure the success of orbital manufacturing and assembly. As history has shown, the stumbling blocks to widespread adoption of technology are not always technological but can be related to legal, regulatory, and other policy-oriented factors. In this vein, we have identified potential legal, regulatory, and policy challenges associated with on-orbit manufacturing and assembly activities.

While no overarching regime is needed for government action (the government is already engaged in R&D precursors to all these activities), if the private sector leads on-orbit manufacturing and assembly-related activities, and especially where human beings are engaged, many issues would need to be resolved. Given that these activities are currently in rudimentary R&D stages, it will be a long time before some of these issues become active deterrents to progress.

The challenges we identified apply almost exclusively to the private sector, and they fall into two categories.

- Legal and regulatory challenges:
  - Licensing of on-orbit activity by government
  - Liability and international dispute-resolution process especially related to accidents
  - Intellectual property, property rights and private businesses protection
  - Compliance with the Outer Space Treaty
  - Compliance with International Traffic in Arms Regulation (ITAR)
  - Other legal and regulatory challenges
- Policy challenges:
  - ISS follow-on policy and greater industry access to the ISS
  - National security concerns
  - Competition from government

a. Licensing

In the realm of space, there is no overarching U.S. licensing regime. The National Oceanic and Atmospheric Administration licenses remote sensing, the Federal Communications Commission licenses spectrum allocations, and the Federal Aviation Administration has authority to establish launch and re-entry, with the State Department and DOD playing supporting roles. However, no agency currently has authority for any other private sector space activities, including on-orbit manufacturing and assembly, or different space mission phases, including moving assets between different orbits. A private company that assembles space satellites independently of the U.S. government has no government supervision, which has relevance to U.S. compliance with the Outer Space Treaty, as discussed subsequently in subsection 4.d.

b. Liability and International Dispute-Resolution Process

Currently, in the United States, on-orbit manufacturing and assembly activities are led by governmental institutions such as NASA, DARPA, or NRO as well as private entities such as SSL, Northrop Grumman, Orbital ATK, Made In Space, or Tethers Unlimited. In this regard, any liability concern would need to cover governmental and non-governmental institutions.

It is important to define under U.S. law to what extent a non-governmental entity would be liable for damages caused in space to a U.S. or a foreign space asset. As with terrestrial systems, there may be a need to develop an international dispute-resolution process for non-government entities, which might request indemnification from other states or private companies. Any legal or regulatory framework should protect the people who work in space, the assets used during on-orbit manufacturing and assembly processes (such as platforms, robots, components, and final products), and third parties and assets that could be damaged during the on-orbit activity. This last issue would become more salient if an on-orbit assembly activity requires moving assets between different orbits. In addition to any legal or regulatory plan, an indemnification process for losses in space should also be developed. Procedures should be established that would apply to the use of the manufacturing/assembly station, to individual actions taken within the station, and to the station provider for any human injury or damage to a space asset.

c. Intellectual Property, Property Rights and Private Business Protection

As on Earth, private entities would require a commitment from the United States to protect their intellectual property and to ensure that their on-orbit manufacturing and assembly businesses and property rights are protected from other licensees' operations. On this front, there is a need to understand how this would fit into the current terrestrial-based intellectual property framework.

d. Compliance with the Outer Space Treaty

Any activity needs to be compliant with the Outer Space Treaty. The specific concern within the Outer Space Treaty comes from Article VI, which establishes that "the activities of non-governmental entities in outer space… *shall require authorization and continuing supervision by the appropriate State Party* to the Treaty"[emphasis added], and Article VIII, which establishes that "a State Party to the Treaty on whose registry an object launched into outer space is carried shall retain jurisdiction and control over such object, and over any personnel thereof, while in outer space or on a celestial body."

No clear or commonly accepted ways ensure that on-orbit activities by private actors are compliant with the treaty (Picard, Nightingale, and Lal 2016). Articles VI and VIII might also be seen by industry as a potential for an increase in regulations that could affect business growth. As discussed previously, it is also unclear which U.S. agency would be in charge of handling this type of monitoring. In its response to Congress on the question of an approach for authorization and supervision that would "prioritize safety, utilize existing authorities, minimize burdens to the industry, promote the U.S. commercial space sector, and meet the United States obligations under international treaties," the Obama Administration developed a legislative amendment to Chapter 509 of title 51, United States Code. The "mission authorization" framework, if implemented, would require "FAA …[to] coordinate an interagency process in which designated agencies would review a proposed mission in relation to specified government interests, with only such conditions as necessary for fulfillment of those government interests." The framework could provide "a clear path for authorization and supervision of new space activities, and encourage investment in those activities and foster and promote a robust domestic commercial space industry."

e. Compliance with Export Control Regulations

Any space activity needs to comply with current domestic regulations such as the International Traffic in Arms Regulations (ITAR), which cover direct defense-related applications, and the Export Administration Regulations (EAR), which cover systems that may have dual-use commercial and defense applications. ITAR and EAR are viewed as limiting interactions between U.S. space companies and their foreign counterparts, which could hinder the business development of U.S. space companies. University research is also subject to ITAR and EAR, which forces universities to control the scientific and technical aspects of their work when collaborating with foreign institutions and students. Obtaining ITAR and EAR approval requires both time and resources, which becomes a bigger roadblock for smaller companies due to their lack of resources. ITAR and EAR also have an effect on the space insurance industry as insurers require technical information from the space object and many insurers are located outside of the United States. It is not clear specifically how ITAR and EAR restrictions may affect the development of on-orbit manufacturing and assembly.

f. Other Legal and Regulatory Challenges

Management of waste generated during on-orbit manufacturing and assembly as well as end-of-life definition for all the tools, platforms, machines, etc., used during the process would require regulations to avoid unwanted debris that could cause damage to other space objects. On orbit-manufacturing and assembly might pose a risk of degradation to the space environment due to the waste and debris produced and the space resources used. These issues would need to be properly addressed within a globally accepted legal and regulatory framework. Public and societal concerns arising from other space users or states due to the use of new, potentially high-risk or hazardous methods, methodologies, or objects in space such as, large robotic structures, harpoons, space tentacles, booms, energy beams, etc., would need to be considered.

5. Industry Partnership and National Coordination

Currently, government investment in on-orbit manufacturing and assembly is in the range of $30 million annually. Private sector levels are not known exactly, but are estimated to be about $10 million annually. The U.S. government could provide incentives to the commercial sector to further invest private-sector funds through a variety of mechanisms. For example, NASA has developed Public-Private Partnership contracts in its Tipping Point programs that are partly supporting orbital manufacturing and assembly-related technologies in activities led by Orbital ATK, Space Systems Loral, and Made In Space.

The government could also provide incentives to the private sector by placing advanced orders that provide some measure of financial stability to commercial companies. Similarly, federal agencies could demonstrate first-in-class capabilities to encourage widespread adoption. This approach appears to be paying dividends in space launch through the advanced support of Space-X and others, and it may provide similar positive effects for orbital manufacturing and assembly.

During the conduct of this analysis, it has become apparent that a wide range of largely unconnected projects cover many aspects of orbital manufacturing and assembly procedures. As we have indicated, several organizations within NASA (Space Technology Mission Directorate, Langley Research Center, Goddard Space Flight Center, and Jet Propulsion Laboratory) are pursuing internal and external R&D of various aspects of on-orbit manufacturing and assembly. And DARPA’s Phoenix and RSGS projects are related to orbital manufacturing and assembly. In some cases, there is significant internal investment by commercial companies. There are likely many benefits that would be derived from greater coordination across parties, especially related to more efficient use of resources, data and information sharing, and planning of critical, but expensive, spaceflight demonstrations.

The R&D effort is currently at a low enough level that informal coordination and collaboration would suffice. Once R&D levels are significant, the community may benefit from more formal coordination mechanisms such as an integrated national strategy. There are many models for such a strategy.[4]

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[4] In addition to SEMATECH, mentioned previously, there is the Brain Research through Advancing Innovative Neurotechnologies (BRAIN) Initiative (http://www.braininitiative.org/), the *National Strategic Computing Initiative Strategic Plan* (https://www.whitehouse.gov/sites/whitehouse.gov/files/images/NSCI%20Strategic%20Plan.pdf), and the *National Artificial Intelligence Research and Development Strategic Plan* (https://www.nitrd.gov/PUBS/national_ai_rd_strategic_plan.pdf).

Appendix A.
List of Interviewees

Table A-1. Names of Interviewees by Affiliation

Affiliation	Name
Air Force Research Laboratory	Greg Spanjers
Boeing	Mark Mulqueen
Defense Advanced Research Projects Agency (DARPA)	Jeffrey Palmer
	Gordon Roesler
Lockheed Martin	Jonathan Chow
	Scott Fouse
	Padrig Maloney
Made In Space	Andrew Rush
NASA Goddard Space Flight Center (GSFC)	Benjamin Reed
NASA Jet Propulsion Laboratory (JPL)	Jason Hyon
	Rudrayan Mukherjee
NASA Langley Research Center (LaRC)	Keith Belvin
NASA Marshall Space Flight Center (MSFC)	Raymond “Corky” Clinton
Northrop Grumman	Jonathan Arenberg
	Alberto Conti
Orbital-ATK	James Armor
	David Kang
Space Systems Loral	Rob Schwarz
	Al Tadros
Tethers Unlimited	Rob Hoyt

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Abbreviations

3D	three-dimensional
AAReST	Autonomous Assembly of a Reconfigurable Space Telescope
AFRL	Air Force Research Laboratory
AIAA	American Institute for Aeronautics & Astronautics
AMD	Advanced Mirror Development
AMF	Additive Manufacturing Facility
ANGELS	Automated Navigation and Guidance Experiment for Local Space
ANSI	American National Standards Institute
AURA	Association of Universities for Research in Astronomy
BBC	British Broadcasting Corporation
BDA	battle damage assessment
CONFERS	Consortium for Execution of Rendezvous and Servicing Operations
comsat	communications satellite
DARPA	Defense Advanced Research Projects Agency
dBi	decibels-isotropic
DEOS	Deutsche Orbitale Servicing
DLR	Deutsches Zentrum fur Luft und Raumfahrt
DOD	Department of Defense
DYNAMIC	Dynamical Neutral Atmosphere-Ionosphere Coupling
EAR	Export Administration Regulations
ESA	European Space Agency
EVA	extra-vehicular activity
FY	fiscal year
GDC	Geospace Dynamics Constellation
GEO	geosynchronous Earth orbit
GSFC	Goddard Space Flight Center
GTO	geostationary transfer orbit
HabEx	Habitable Exoplanet Imaging
HDST	high-definition space telescope
HST	Hubble Space Telescope
IBEX	Interstellar Boundary Explorer
IDA	Institute for Defense Analyses
IMAP	Interstellar Mapping Probe
INSPECT	Integrated Navigation Sensor Platform for EVA Control and Testing
IRAD	Independent Research and Development
ISR	intelligence, surveillance, and reconnaissance

ISRU	in situ resource utilization
ISS	International Space Station
ITAR	International Traffic in Arms Regulations
IXO	International X-ray Observatory
IXV	Intermediate Experimental Vehicle
JAXA	Japan Aerospace Exploration Agency
JPL	Jet Propulsion Laboratory
JWST	James Webb Space Telescope
kg	kilogram(s)
LaRC	Langley Research Center
LEO	low Earth orbit
LISA	Laser Interferometer Space Antennae
LUVOIR	Large Ultraviolet Optical Infrared
m	meter(s)
MDA	MacDonald, Dettweiler, and Associates
MEDICI	Magnetospheric Energetics, Dynamics, and Ionospheric Coupling Investigation
MELT	Manufacturing of Experimental Layer Technology
MEV	Mission Extension Vehicle
MIT	Massachusetts Institute of Technology
MSFC	Marshall Space Flight Center
MW	missile warning
NASA	National Aeronautics and Space Administration
NRC	National Research Council
NRO	National Reconnaissance Office
OBSS	Orbital Boom Sensor System
OTA	Optical Telescope Assembly
PRIDE	Program for a Reusable In-orbit Demonstrator for Europe
R&D	research and development
RSGS	Robotic Servicing of Geosynchronous Satellites
SBIR	Small Business Innovation Research
SLS	Space Launch System
SSL	Space Systems Loral
STMD	Space Technology Mission Directorate
STPI	Science and Technology Policy Institute
TALISMAN	Tension-Actuated Lightweight In-Space Manipulator
W	watt(s)
WFIRST	Wide Field Infrared Survey Telescope