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Assessing Potential Demand for Orbital Outposts

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Executive Summary

Introduction

Government agencies and companies have recently expressed interest in the development of an uncrewed, persistent platform in space. The Department of Defense (DoD), through the Defense Innovation Unit (DIU), has funded several projects to create such platforms, which they call orbital outposts. DIU has also funded the development of multi-orbit logistics capabilities that would support such an outpost. An outpost could potentially support government, industry, and academic needs for in-space testing of space systems, refreshing technologies on operational satellites, microgravity research and development (R&D), in-space manufacturing and assembly of products, deployment of space assets more rapidly than possible using launch vehicles, and other applications. The purpose of this study is to assess the feasibility and potential cost-effectiveness of using orbital outposts, as opposed to alternative methods for access to space, to support a variety of these use cases.

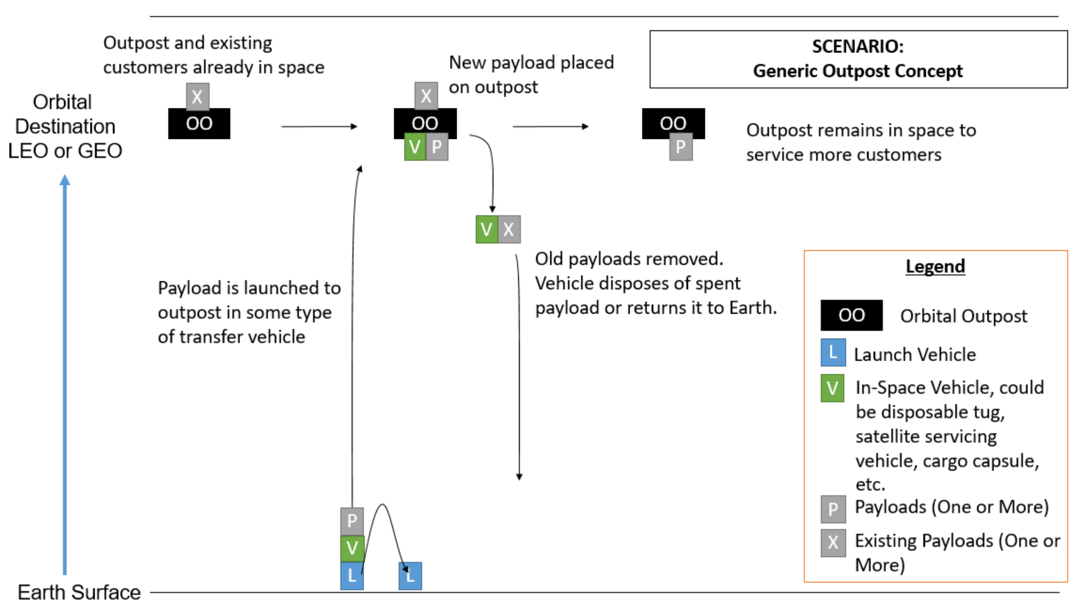


Figure ES-1. Generic Concept of Operations for an Orbital Outpost

For the purposes of this study, we define an orbital outpost as a persistent, uncrewed platform in space capable of adding or replacing payloads on orbit without interrupting the platform's operations. A generic concept of operations for such an outpost is shown in

Figure ES-1. Using an outpost, it may become possible for the payload to be launched without being first integrated into a bus. Upon arrival at the outpost on orbit, the payload would be integrated with the outpost, receiving mission services from the outpost operator as necessary. When the mission ends, the payload owner stops paying for services from the outpost, opening up opportunities for other paying customers to use the vacated space.

Traditionally, an organization that wants to design and fly a payload in space must build and operate a satellite that hosts that payload. Payload operators become responsible for purchasing a satellite bus and other subsystems; integrating their payload into the bus; securing their own telemetry, tracking, and control solutions; procuring launch services; applying for a spectrum license from the Federal Communications Commission (FCC); and operating both the bus and the payload throughout the mission and through disposal. Using an outpost, the payload owner may be able to focus just on developing the payload, potentially avoiding many of the costs associated with the traditional paradigm.

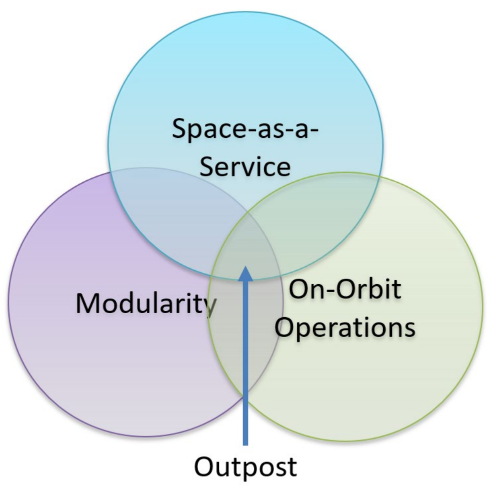


Figure ES-2. Orbital Outpost Is the Convergence of Three Emerging Space Capabilities

The value provided by an orbital outpost derives from the convergence of three emerging types of space capabilities, as shown in Figure ES-2. One capability is satellite modularity. Historically, efforts to develop this capability have focused on modularity and standardization of the spacecraft subsystems such as communications and attitude control. An outpost would require further modularity and standardization related to payloads and their interfaces. Another capability is on-orbit operations supported by robotic manipulation capabilities. While some robotic arms have been demonstrated in space, none of them were produced in the United States. There is little doubt that the space industry can build robotic arms capable of performing the tasks needed for an orbital output; however, it remains to be seen whether such arms can be produced and operated at cost points that allow for broad commercial usage. The final capability is space-as-a-service

(SpaaS). SpaaS is an emerging paradigm for reducing the cost of space access where payload owners focus only on the development of their payload and a satellite operator handles everything else.

Methodology

To assess the utility of orbital outposts, we compare their ability to perform various activities in space with the abilities of alternative platforms. We use a scenario-based approach. We distill potential outpost operations into four high-level scenarios based on the four types of buses around which they are built (Figure ES-3). The building block scenario uses a small satellite bus, a single robotic arm, and does not provide pressurized volume. The condo satellite scenario uses a large bus typically used for geosynchronous (GEO) satellites—though it may be launched to any orbit—two robotic arms, and does not provide pressurized volume. The capsule and traditional module scenarios are based on cargo capsules and International Space Station (ISS)-modules, respectively. In these last two scenarios, each outpost uses two robotic arms and provides pressurized volume, though the buses do not have environmental control and life support services (ECLSS) to support crew.

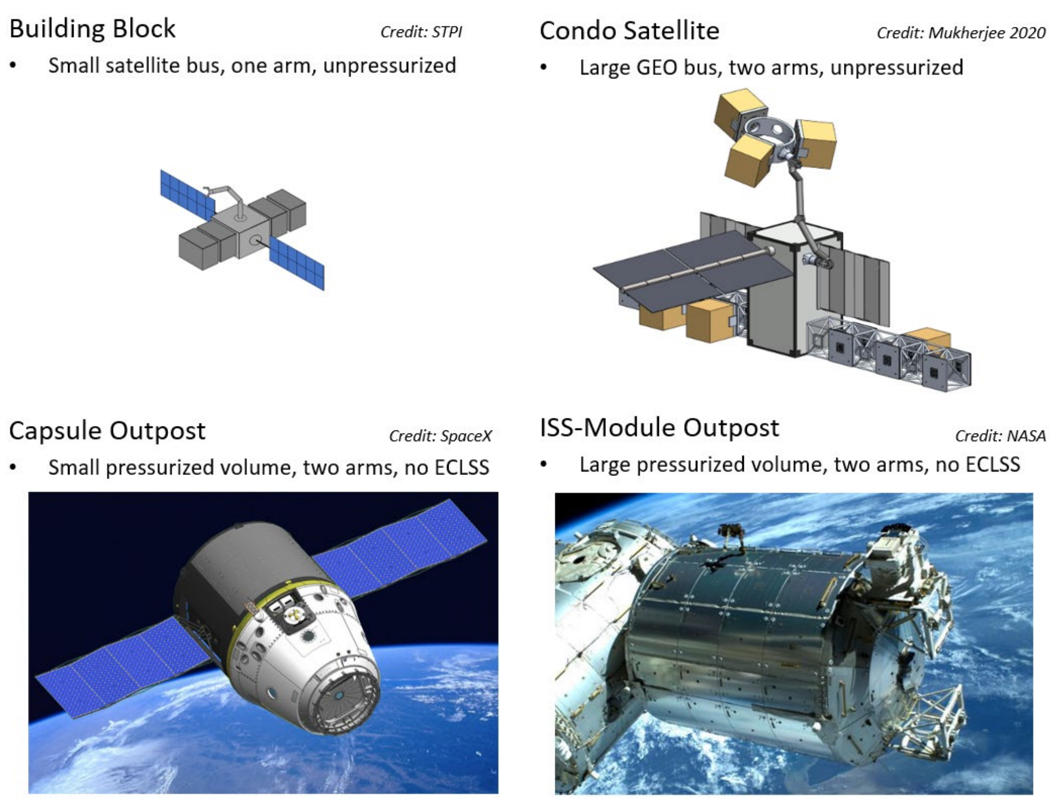


Figure ES-3. Outpost Scenarios Considered

We compare the outpost scenarios with alternative scenarios for future space access. One alternative is to use a disposable orbital transfer vehicle (d-OTV) that can host payloads after delivering other customers to their final orbits. We also investigate the use of a reusable orbital transfer vehicle (r-OTV)—a space tug with robotic arms that can be refueled—for hosting payloads while not servicing other customers. We develop a scenario where payloads are hosted in a reusable cargo vehicle, such as a SpaceX Dragon or Sierra Nevada Dream Chaser, which repeatedly launches and returns to Earth. Finally, we also consider scenarios where the payload is simply integrated into a satellite on the ground before being launched.

We characterize potential space activities and compare the use of the outpost scenarios versus the use of the alternative scenarios for performing the activity. Our main point of comparison is cost; however, we also consider schedule, risk, and other potential factors. We assume that all future platforms of interest will use SpaaS due to the potential for reduced costs and operational risk. Further, we assume the payload owner has developed the payload—it is a sunk cost in terms of funds and schedule—and attached it to a standardized interface to ease subsequent integration into the bus. With payload ready and in hand, the payload owner is shopping for a SpaaS provider.

We use interviews, space-industry news sources, and journal articles to identify the potential activities that an outpost might perform, the scenarios for outposts and alternatives to perform those potential activities, and for some of the costing information. We conducted 30 interviews, including 4 companies that may provide outpost services in the future; 5 companies offering alternative services that will compete with outpost providers; 7 subject matter experts regarding the costs associated with various space components and details regarding potential activities that could be performed on an outpost; and at least 1 organization that may be a potential user of an outpost within each of the space activities that we consider. For our cost estimates of each scenario, we also rely heavily on Federal procurement data of analogous systems and QuickCost 6.1, a parametric cost model for space missions, developed by a former Director of Cost Analysis for the National Aeronautics and Space Administration (NASA).

Our approach prioritizes the ability to analyze a broad landscape of space utilization, making apples-to-apples comparisons as much as possible. This landscape-level view introduces some limitations. For instance, we use a highly simplified cost model for space hardware and for launch costs. Further, we could not look at all possible SpaaS scenarios, potential space activities, or combinations of scenarios and activities. We attempt to be as comprehensive as possible, but we could not be exhaustive. We use a logical framework to provide a look at the potential future of the space industry, but our assessments are not predictive or definitive.

Results

We apply our methodology to five major classes of space activities. **In-Space Test and Demonstration** is the ability to test space systems or subsystems in their intended operational environment. **Technology Refresh** is the ability to upgrade the hardware on an operational satellite, either to improve existing capabilities or to repair a faulty subsystem, without building and launching a replacement satellite. **Microgravity R&D** services provide access to the space environment—i.e., microgravity, vacuum, and radiation—to the research community. **Manufacturing for Earth Customers** is the use of the space environment to produce products that will be sold in terrestrial markets. There are other classes of space activities that we were unable to analyze with our methodology; for these, we provide qualitative thoughts based on our findings for the analyzed activities. We summarize our results in Table ES-1.

Table ES-1. Summary of Findings

Space Activity	Demand Assessment
In-Space Test and Demonstration	
Test space subsystems, such as batteries, solar panels, propulsion, etc.	In most cases, there is no need for a test payload to transfer off the d-OTV that carries it to space.
Repeatedly demonstrate applications with high-value, high-mass test articles	Building block significantly outcompetes alternatives. Revenue opportunities may exist for demonstrating robotic manipulation, in-space assembly, and in-space manufacturing.
Expose test articles to adverse environments	Building block might outcompete a stand-alone satellite if it has a large overlap with operational DoD satellites and if DoD requires an extensive test campaign.
Technology Refresh	
Replace or upgrade an instrument on a small satellite	Outpost is unlikely to be competitive with simply launching a new satellite.
Replace or upgrade one or more instruments on a large satellite	Condo satellite can save hundreds of millions of dollars and reduce operational risk compared to launching a new satellite.
Microgravity R&D	
Experiments that do not need to return material to Earth	Building block has a narrow path to outcompete CubeSat missions, albeit with many caveats.
Experiments that require mass to be returned to Earth	Capsule and module outposts have a narrow path to outcompete alternatives if demand for R&D were substantially greater than current levels and NASA subsidies encouraging use of the ISS were altered.

Space Activity	Demand Assessment
Manufacturing for Earth Customers	
High performance fiber optic cables, such as ZBLAN	Producing the cables in a cargo vehicle is preferable. Costs are similar to the use of an outpost, but the production machinery is frequently returned to Earth for maintenance.
Biological products, such as printed human organs	Printing organs on a module outpost is cheaper than doing so in a cargo vehicle. The cost per organ is much greater than current prices, but customers are likely willing to pay.
High purity semiconductors, such as silicon carbide	This activity is not suitable for an outpost. It requires a high purity vacuum that would be polluted by other customers and possibly the outpost itself.
Other Services[a]	
On-orbit manufacture and assembly of space assets, such as space telescopes	Outpost might provide value compared to a platform dedicated to satellite assembly. Value may exist in GEO, but there are unlikely to be sufficient customers in low-Earth orbit (LEO).
Printing spare parts for a crewed platform	A 3D printer installed on a crewed platform is likely to be faster and cheaper than one installed on an outpost.
Home base for a satellite-servicing vehicle	Building block may store consumables, such as propellant or tools, for a satellite servicer in GEO. Just-in-time delivery of consumables may be preferred in LEO.
Space domain awareness services	Outpost might be appropriate for hosting observational assets.
Orbital range for realistic training and exercising of service members	Training and exercising is more likely to be satisfied by a virtual range than flying physical space hardware.

a. We were unable to assess these services using our methodology. We provide a qualitative discussion instead.

Viability of Outposts

The most promising application for an outpost is to perform technology refresh of large satellites. This use case is somewhat future-proof to the effects of large reductions in the cost of launch. Even if launch costs go to zero, some satellites still represent a substantial investment in hardware that would justify the cost of a repair or upgrade. However, in this case, a single-tenant (single customer) model appears more attractive than a multi-tenant model. A challenge with realizing the benefits of this use case is that it may be difficult to "start small" because smaller platforms may not justify the cost of performing an upgrade or repair.

The best use of a small outpost, using a multi-tenant model, is likely for demonstrating applications, when an expensive or massive piece of hardware is aboard the outpost that many different users would like to utilize. We examined the situation where the robotic arm on the outpost is itself the subject of experimentation and found that robotic arm experiments in space have the potential to be affordable through Small Business Innovation Research grants and small R&D projects funded by government laboratories. If these sources of funds are needed to make testing economical, the government would be required to be an anchor customer to coordinate a portfolio of R&D funding around the capabilities installed on the outposts.

For other potential use cases an outpost will face stiff competition from other platforms. Revenues may be possible, but the majority of customers for these services may be better served by other platforms. As a destination that simply provides power, communications, pointing, and thermal management, an outpost tends to be more costly and riskier than using a short-lived, disposable platform that also provides those capabilities.

The main value of developing outpost technologies is the maturation of modularity and SpaaS capabilities. In a future where those two capabilities are mature, space platforms without robotic arms and capabilities for rendezvous and proximity operations (RPO) generally outcompete platforms that include these costly additions. Modularity and SpaaS capabilities have the potential to reduce the cost and complexity of space access from the user's perspective, benefiting the entire space enterprise.

Drivers of Demand

The first orbital outposts may become operational approximately 5–10 years from now. Many factors could influence demand for such a platform over the next few decades. Decreasing costs of space access will have a mixed effect on the viability of orbital outposts. On the one hand, lower launch costs may bring more customers into space and reduce the cost penalties associated with modular satellites, which are more massive than custom-built satellites. On the other hand, an extreme drop in the cost of returning mass to Earth, such as advertised by the SpaceX Starship, may undermine the outpost's competitive niches. In this case, there is no longer a strong incentive to store expensive or massive machinery in space or to refresh technologies in space; it can be brought back down every time for little cost. As a thought experiment, a platform like Starship might be able to capture a damaged satellite, return it to Earth for repairs, and then launch the refurbished satellite back into orbit. This exact feat was demonstrated in 1984 when the Space Shuttle returned the Westar 6 satellite to Earth for refurbishment and relaunch.

Increasing use of proliferated satellite constellations will also have a mixed effect. As the industry moves away from single expensive platforms to numerous low-cost platforms, there is a reduced incentive to repair or upgrade individual satellites. However, two of the motivations for launching large numbers of small satellites are to have the ability to refresh technologies more regularly and to increase the robustness of space services. Both of these effects can be achieved with an orbital outpost; thus, broad adoption of outpost technology may reduce the incentive for proliferation.

Tighter rules concerning orbital debris and space traffic management are likely to benefit the case for orbital outposts. The FCC has the responsibility for regulating orbital debris and post-mission disposal plans for commercial companies. Some of its proposed regulations would make it more difficult for d-OTVs to perform some of the space activities where they are currently most competitive. Likewise, some of the FCC's proposed rules may make small satellite operations more costly or impractical. Payloads that currently would be flown on small satellites, especially CubeSats, could be hosted together on an outpost, which would make de-orbiting all of the payloads relatively easy and likely faster than as free-fliers.

A government supported and subsidized platform, like the one being pursued by NASA's Commercial LEO Destinations (CLD) program, will attract potential customers away from outposts. A crewed platform may be able to generate revenues from hosting space tourists or government astronauts. While these revenues alone are unlikely to cover costs of such a platform, when combined with development and operational subsidies from NASA, the platform may be able to offer other services at price points that compete with a robotically tended outpost.

Recommendations

Government investments should focus on the development of the supporting services required for an outpost: SpaaS, satellite modularity, and satellite servicing. As these technologies mature and the utility of their use cases are proven (or disproven), their economic viability will become clearer. Once these capabilities are mature, government or private providers can determine whether a stand-alone outpost is valuable to pursue or whether existing SpaaS, modularity, and servicing capabilities are sufficient. We see the creation of an orbital outpost as happening organically and without further government support, once these three supporting capabilities are developed. To implement this, we make the following recommendations.

Use Acquisition and Development Contracts to Support Satellite Modularity. This capability is likely to reduce the cost of space access whether payloads are integrated in space or on the ground. The most fruitful method of support would be for both DoD and NASA to commit to using modular buses for a specified number of future missions.

Develop Standards with Industry, Academia, and International Partners. Satellite modularity and SpaaS capabilities may falter without an agreed set of standardized interfaces around which the industry designs. The U.S. Government should convene foreign and domestic stakeholders from industry, academia, and government to develop the standards required for modularity of satellite subsystems and payloads.

Cultivate a Network of SpaaS Providers and a Single Point of Contact at Agencies. DoD and NASA can encourage the use of SpaaS by identifying current and emerging SpaaS providers, then ensuring that programs developing space hardware are acquainted with the services of those providers. An initial step to encouraging the use of SpaaS may be to increase the resources available to DoD's Space Test Program and to broaden its mission to include supporting the development of emerging SpaaS capabilities.

Proactively Engage on Orbital Debris Guidelines and Regulations. The development of these rules appears to be more focused on reducing the amount of orbital debris and less on the role these regulations may play in supporting the emergence of future space-based markets. DoD and NASA could encourage new rules that support emerging businesses' activities that may benefit from using outposts. For instance, vehicles that perform active debris removal may wish to use an outpost as a home base to cache propellant or other consumables; however, FCC's proposed regulations do not allow active debris removal as a viable method for post-mission disposal.

Coordinate Satellite Servicing Development with Outpost Development. The scenarios we analyzed that used high-cost robotic arms and high-cost RPO capabilities were not competitive with alternatives. DoD and NASA should consider ways to reduce the costs of satellite servicing that also support the emergence of an outpost. For instance, DoD and NASA could coordinate a joint research portfolio that advances satellite-servicing capabilities and that could only be performed on a persistent platform in space.

Consider Requirements for In-Space Testing. Without a requirement for subsystem, operational, or adverse events testing in space, an outpost is unlikely to see broad adoption for these purposes. As a first step toward the development of acquisition requirements, DoD should commission an independent assessment to identify missions that are vulnerable due to a lack of in-space testing and further identify the specific types of in-space testing capabilities that would be needed to address the vulnerability.

Communicate with the International Community. Considering DoD's support of persistent orbital platforms, the U.S. Government should make a coordinated effort to engage with the international community about their use. Outposts may present an opportunity for cooperation in space with our allies and for attracting new international partnerships in space. The international community is concerned with the potential weaponization of space. While the orbital platform is not intended to conduct weapons testing in space, a perception that it does could become a diplomatic issue.

Contents

1. Introduction

A. Purpose

Government agencies and private companies have recently expressed interest in the development of an uncrewed, persistent platform in space. For instance, the Defense Innovation Unit (DIU) has funded several projects to create such platforms, which they call orbital outposts, along with multi-orbit logistics capabilities that would support an outpost. An outpost could potentially support government, industry, and academic needs for in-space testing of space systems, refreshing the technology on operational satellites, microgravity research and development (R&D), in-space manufacturing and assembly of products, deployment of space assets more rapidly than possible using launch vehicles, and more. The purpose of this study is to assess the feasibility and potential cost-effectiveness of using orbital outposts, as opposed to alternative methods for access to space, to support a variety of use cases. The study also makes recommendations for how the U.S. Government can support the development of orbital outposts.

B. Background

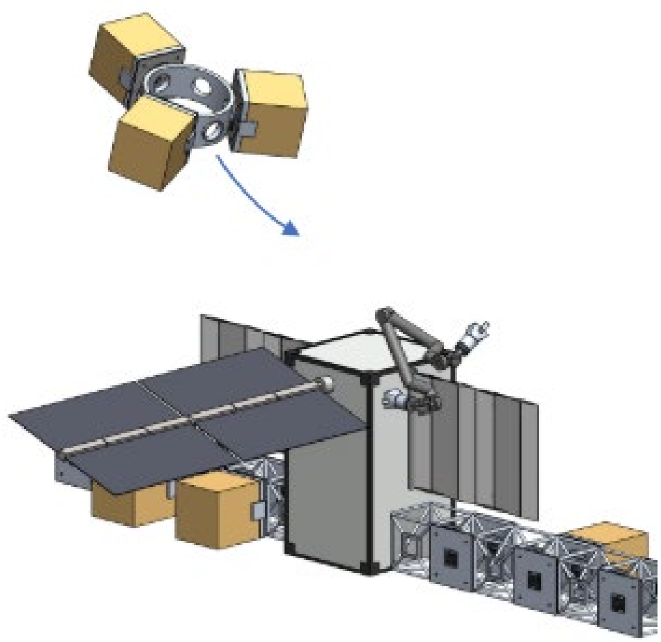
1. What Are Orbital Outposts?

In July 2019, DIU sought proposals for a self-contained and free flying "orbital outpost." The request specified that the outpost "must be capable of supporting space assembly, microgravity experimentation, logistics and storage, manufacturing, training, test and evaluation, hosting payloads, and other functions." The outpost must have guidance, navigation, and control for sustained free-flight operations. Favorable characteristics of an outpost include modularity and scalability. DIU gave the minimum desired specifications as:

- Internal Volume: 1 cubic meter;
- Payload capacity: 80 kilograms;
- Electric Power (continuous): 1 kilowatt;
- Communications: 100 kilobits per second; and
- Pressurization: 0 to 1 atmosphere.

While not required for the initial iteration, DIU expressed the desire that future iterations of an outpost could support in-space assembly using one or more robotic manipulators and interfaces accepting standard flight fixtures. Future outposts may be able to attach to other outposts either temporarily or permanently. They might also become human rated with crew quarters and a common berthing mechanism, or at least be able to dock with other crewed platforms. Outposts are also envisioned to become sufficiently radiation hardened to operate beyond low-Earth orbit (LEO).

Based on the above specifications, we define an orbital outpost for this study as a persistent, uncrewed platform in space capable of hot-swapping[1] payloads on orbit. This platform may be any size and may or may not provide pressurized volume. Figure 1 shows an example that is the size of a satellite commonly found in geosynchronous (GEO) orbits. An outpost can host multiple customers simultaneously, with customers coming and going as needed. While onboard, the customers will pay for services that the outpost provides, such as electricity, propulsion, thermal management, communications, radiation protection, pointing, and pressurized volume. The provision of these services can be provided contractually or as part of a governmental function. The outpost provides a platform for hosting and operating payloads, allowing its customers to focus only on the development of their payload and to save costs related to satellite manufacturing and operations.



Source: Mukherjee 2020

Figure 1. A CondoSat Outpost, as Envisioned by Mukherjee.

[1] In this context, hot swapping is the addition or replacement of components on a space vehicle while the vehicle is operational. The process can be performed without interrupting the vehicle's operation.

Any system or platform that does not have the above characteristics is not considered an outpost for the purposes of this study. For example, a typical satellite may be designed to stay in space and host multiple payloads, but those payloads are typically not designed to be swapped out on orbit, so it is not an outpost. The International Space Station (ISS) hosts many payloads that are exchanged on orbit, but it is a crewed platform, thus it is not an outpost for the purposes of this study. For clarity, a space platform that has the capability to exchange payloads on orbit but never actually does so is still considered an outpost. A reusable cargo vehicle that returns to Earth to swap its payloads is not considered an outpost; an outpost must operate in space for its entire lifetime.

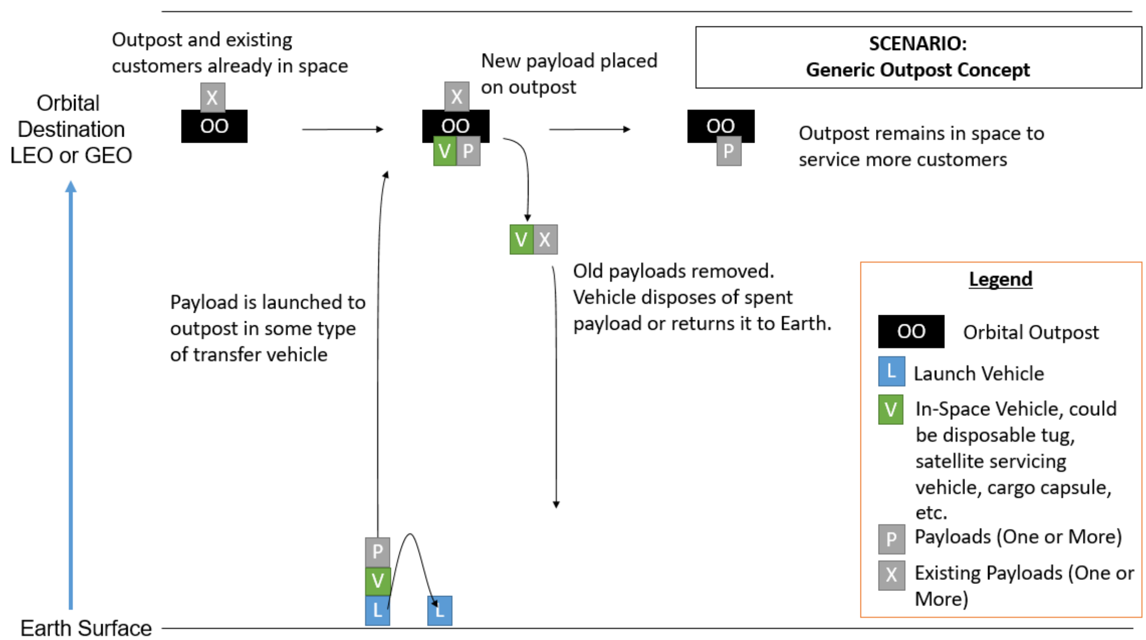


Figure 2. Generic Concept of Operations for an Orbital Outpost

A generic concept of operations (CONOPS) for an outpost is shown in Figure 2. With an outpost already in its destination orbit, a launch vehicle and an orbital transfer vehicle (OTV) can deliver a new payload to the outpost. The OTV may be launched with the payload or it may be a previously launched satellite-servicing vehicle (not shown) that picks up the payload from the launch vehicle at a drop-off point in space. Upon delivery to the outpost, the payload will be attached and begin its operations. Other payloads may have been previously attached to the outpost and have now completed their mission. These existing payloads can be transferred to the OTV for return to Earth or disposal via reentry.

2. Potential Advantages of Orbital Outposts

Historically, an organization that wants to design and fly a payload in space must build and operate a satellite that hosts their payload. Payload operators become responsible for purchasing a satellite bus and other subsystems; integrating their payload into the bus; securing their own telemetry, tracking, and control (TT&C) solutions; procuring launch services; applying for a spectrum license from the Federal Communications Commission (FCC); and operating both the bus and the payload throughout the mission and through disposal. For simple payloads, the costs associated with becoming a satellite operator are generally much greater than the costs of developing the payload itself. Moreover, a scientist or engineer that knows how to build a specific, specialized space instrument is unlikely to also know how to design the satellite, imposing a steep learning curve that must be overcome to develop a satellite that operates successfully.

Using an outpost, it may become possible for the payload to be launched without being integrated into a bus. Upon arrival at the outpost on orbit, the payload would be integrated with the outpost, receiving mission services from the outpost operator as necessary. When the mission ends, the payload owner stops paying for services from the outpost, opening up opportunities for other paying customers to use the vacated space.

Under this paradigm, payload owners may substantially reduce costs and risks by avoiding the upfront costs of integrating their payloads with a bus and paying only for the launch of the payload mass instead of the more-massive fully integrated bus. In the case of a failure, payload owners may have substantially limited their losses, which could leave them with sufficient resources to rebuild their payloads and fly again. Similarly, payloads hosted on an orbital outpost can be updated more easily if a technology refresh is required, as updated modules can be launched to the outpost and swapped out over time. By launching only the payload and not a larger integrated bus, it may become easier to leverage small-launch vehicles or to take advantage of ride-sharing opportunities—thus, decreasing the waiting time for a payload to fly. Using an outpost, it may be possible to reduce mission costs, shorten mission schedules, and increase flexibility for payload owners.

3. Challenges to the Use of Orbital Outposts

An orbital outpost is one among many methods of providing access to space. To be competitive, an outpost must offer services at a cost that is competitive with other emerging options for space access. There are several technical challenges involved with orbital outposts that are not present in other emerging services. These include in-space logistics, interface control, and the use of robotic arms.

The repeated exchange of payloads, first between the delivery vehicle and the outpost, then between the outpost and the disposal vehicle after the mission concludes, increases operational risk. Maintaining and refreshing payloads on an orbital outpost requires the capability to perform rendezvous and proximity operations (RPO) on either the outpost or the payload delivery vehicle. RPO requires precision instrumentation to match orbits between the outpost and delivery vehicle—the more capable the delivery vehicle, the more expensive the in-space logistics. Tight coordination among the outpost and in-space logistics providers is likely required, along with in-space robotics to transfer payloads between the delivery vehicle and the outpost and to remove payloads from their assigned slots on the outpost. Space-rated robotic arms are expensive, especially ones with long lifetimes and high reliability. Whether there is one outpost and logistics provider or a marketplace of many, interface control will be difficult, especially among multiple entities. Coordination among various in-space logistics providers may be difficult, and no providers or users would want to be in a situation where each outpost, logistics vehicle, and payload has its own set of interface standards.

Orbital outposts will face competition from both satellite service providers and an existing outpost, the ISS, which currently heavily subsidizes its users. Certain payloads may have requirements that can be satisfied by an inexpensive small satellite bus or by the logistics vehicle that would deliver the payload to the outpost. This is doubly true for payloads that must return to Earth intact; short-duration payloads that require return mass may be able to satisfy their requirements without being offloaded to an outpost.

C. Methodology

To assess the utility of orbital outposts, we compare its ability to perform various activities in space with the abilities of alternative platforms. In this section, we describe how we estimate the costs associated with outposts and alternative platforms, choose the activities for our comparisons, and the methods by which we make the comparisons. We spend substantial time discussing some of the major assumptions underpinning our analysis.

The value provided by an orbital outpost is due to the convergence of three emerging types of space capabilities, as shown in Figure 3. One capability is satellite modularity. Historically, efforts at developing this capability have focused on modularity and standardization of the spacecraft subsystems such as communications and attitude control. An outpost would require further modularity and standardization related to payloads and their interfaces. Another capability is on-orbit operations. While some robotic arms have been demonstrated in space, none of them were produced in America. Further, the types of in-space robotic manipulation required for hot-swapping payloads on orbit have not yet been demonstrated. There is little doubt that industry can build robotic arms capable of performing the task; however, it remains to be seen whether such arms can be produced and operated at cost points that allow for broad commercial usage. The final capability is space-as-a-service (SpaaS). SpaaS is an emerging paradigm for reducing the cost of space access where *payload owners* focus only on the development of their payload and a *satellite operator* handles everything else.

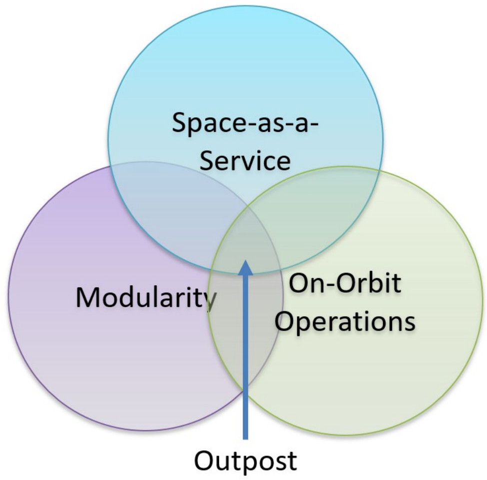


Figure 3. Orbital Outpost Is the Convergence of Three Types of Space Capabilities

1. Data Sources

We use interviews, space-industry news sources, and journal articles to identify the potential activities that an outpost might perform, the scenarios for outposts and alternatives to perform those potential activities, and for some of the costing information. Table 1 shows a high-level breakdown of the 30 interviews we conducted. We spoke with four different companies that may provide outpost services in the future; we engaged with some of these companies repeatedly. We spoke with five companies we identified as offering services that will compete with outpost providers. We engaged with seven subject matter experts regarding a range of topics, mainly regarding the costs associated with various space components and details regarding potential activities that could be performed on an outpost. Finally, for each of the space activities that we consider, we spoke with at least one organization that may be a potential user of an outpost. Questions for potential users focus on what their mission needs are and their considerations for choosing between an outpost and other methods of space access.

Table 1. Summary of Interviewees

Type of Interviewee	Count
Outpost Operator	4
Alternative	5
Subject Matter Expert	7
Potential User	14
Grand Total	**30**

To develop cost and performance estimates for spaceflight hardware, we rely on three types of sources. We rely heavily on open source news articles, interviews with industry representatives, journal articles, and company websites. These sources sometimes explicitly state relevant costs and performance metrics. We also rely heavily on Federal procurement data, as provided by the Defense and Aerospace Competitive Intelligence Service (DACIS). While this data is technically open source, it is too difficult to access without a subscription to a service that archives and provides analytics on the data. For places where we leverage data found in DACIS, we generally cite the relevant Federal contract number, which can be used to find the contract data using any internet search engine—a DACIS subscription is not required. Finally, we infrequently invoke insights gathered from the QuickCost 6.1 tool. QuickCost is parametric cost model for space science missions implemented in Microsoft Excel (Hamaker 2016). The tool was developed by Joe Hamaker, a former Director of Cost Analysis for the National Aeronautics and Space Administration (NASA) at NASA Headquarters.

2. Assumptions

We make a number of simplifying assumptions. We believe these are necessary to make the analysis tractable. In this section, we describe and justify the major assumptions.

a. All Potential Customers of an Outpost Have Decided to Use SpaaS

As discussed above, under the traditional paradigm for launching a payload into space on a satellite, an organization that wishes to fly a payload for any purpose must effectively become a satellite owner and operator. Under the SpaaS paradigm, the satellite operator takes delivery of the payload, charges the payload owner a fee for handling all of the associated integration and operations costs, and provides the data or other services back to the payload owner.

Compared to the traditional paradigm, payload owners using SpaaS can reduce their costs and accelerate their schedules. Specifically, the payload owner avoids the costs and time associated with learning to become a satellite integrator and operator. Further, payload owners pay for only the services that they use. For example, if the payload owner had to pay for a full satellite with a lifetime of 3 years, but only needed their payload to be on orbit for 6 months, the owner would be paying for 2.5 years of excess satellite lifetime. A satellite operator offering SpaaS can bundle payloads together to efficiently distribute costs across various payload owners according to their usage needs. Similarly, the effects of a satellite or payload failure can be mitigated. Some SpaaS providers do not charge payload owners until the services have been rendered. If the satellite fails, the payload owner pays nothing. If the payload fails, the payload owner can terminate its service to avoid further charges.

An orbital outpost is clearly an advanced concept for providing SpaaS. In this analysis, **we assume that all potential customers of an outpost have already decided to pursue the cost and schedule benefits of using SpaaS**. This assumption is necessary because if a payload owner is not willing to use SpaaS, then they are not willing to use an orbital outpost. Conversely, if a customer has agreed to consider using an orbital outpost, then they will also consider alternative methods of space access that address the needs of their mission. Thus, the crux of our analysis is to estimate the competitiveness of an orbital outpost as compared to alternative methods for providing SpaaS. If an outpost cannot provide cost, schedule, flexibility, or other benefits that outcompete alternatives, then it will not be providing a valuable service for potential customers.

b. Payloads Are Already Built and Attached to a Standardized Interface

An important consequence of our assumption that all potential users will use SpaaS is that the cost of developing the payload becomes irrelevant to our analysis.[2] **We assume the payload owner has developed their payload**—it is a sunk cost in terms of funds and schedule—**and attached it to a standardized interface** to ease subsequent integration into the bus. In other words, the payload is a module that can be attached to a modular spacecraft. With payload ready and in hand, the payload owner is shopping for a SpaaS provider. Thus, we focus our analysis on the costs and relative benefits among orbital outpost concepts and other potential SpaaS architectures.

c. Hardware and Launch Costs Are the Differentiators among SpaaS Scenarios

We do not estimate the total cost associated with each scenario; instead, **we assume that only the unit costs of the space vehicle's hardware and its launch costs are the significant differentiators between SpaaS scenarios**. Other costs associated with the development of the spacecraft, development of the payload, project management, systems engineering, satellite integration, on-orbit operations, and ground systems are omitted wherever possible because their inclusion will not be a dominant effect in the determination of which scenario is the most cost effective.

It is reasonable to omit development costs because all SpaaS scenarios rely on immature capabilities. For instance, all companies must develop advanced satellite modularity and we have no reason to assume that one company can develop the needed capability more cheaply than another company can. Development costs could be estimated by relating them to the unit costs of the hardware. If a heuristic relating the two costs were applied uniformly across all scenarios, all scenarios would increase in cost by roughly similar percentages; their relative cost competitiveness for customers would not change. Further, the U.S. Government may support the development of different systems to varying degrees; comparing systems with their full development costs incorporated may be somewhat misleading when making comparisons between systems. For instance, the Sierra Nevada Dream Chaser and SpaceX Dragon have received significant government support

2 There is one exception, which is the technology refresh use case discussed in Chapter 3.

already, while other systems currently under development have not. Similar arguments apply for the omission of project management and systems engineering costs.

Costs associated with the development of the payloads are generally the same for all platforms. As mentioned previously, we assume that the payloads are attached to a standard modular interface; the payload owner has already sunk this cost. Likewise, we assume that costs associated with integration of the payload into a satellite or orbital outpost are effectively the same for any given customer. For instance, if a payload can be easily integrated in-space, it can be just as easily integrated on the ground. We assume that all SpaaS providers will have sufficient—though not necessarily equal—satellite modularity capabilities that integration costs are not a differentiator between scenarios.

Operations associated with the space and ground segment of each scenario may be significant; however, we do not expect them to be cost differentiators at this point. Similar to our discussion of development costs, one approach to estimating operations costs is to consider it a percentage of the development or hardware costs. In such a case, hardware costs are again the driving factor of the *relative* cost competitiveness.

Differences in some of these cost elements may vary based on the payload. For instance, the modularity, integration, and operation associated with a complex scientific instrument may be more costly than for a simple, low-cost instrument; however, any platforms that wish to host the complex instrument will need to incur approximately the same costs to satisfy that type of payload.

Omission of these costs likely biases our estimates in favor of an orbital outpost. For instance, outpost scenarios generally require the use of robotic arms, which are still under development; scenarios that do not require the use of robotic arms would not incur such costs. Likewise, the costs associated with operating robotic arms in space and hot-swapping payloads on orbit are likely greater than the operations costs associated with SpaaS scenarios that are substantially less complex. If an outpost scenario is not cost competitive under our assumptions, it is unlikely to become cost competitive in a higher fidelity cost analysis.

d. Customers Require Access to Orbit

We assume that the payloads and missions we analyze truly require access to an orbital space environment. This assumption is clearly valid for some potential activities; however, the assumption only tenuously holds for others. For instance, many microgravity experiments can be performed using drop towers or suborbital flights. It is beyond the scope of this analysis to validate the need for orbital space access for each of these activities. Therefore, we operate under the assumption that within each activity of interest, there are some customers whose needs cannot be satisfied by terrestrial or suborbital facilities.

3. Process for Assessing the Utility of Outposts Compared to Alternatives

a. Develop Scenarios for Space Access Using Outposts and Alternatives

We develop a set of scenarios for providing access to space using SpaaS. These include the use of orbital outposts and alternative approaches that do not require an outpost. Alternative approaches include the use of small stand-alone satellites, cargo capsules, spaceplanes, the ISS, etc. For each scenario, we describe the capabilities provided, illustrate the concept of operations for its use, and estimate its associated costs.

b. Characterize Potential Space Activities for an Outpost to Perform

We list the main activities that outposts might be able to support in space. These activities include current activities in space and proposed activities from government agencies, supplier companies, and other stakeholders in the space community. In addition to listing the activities, we identify which groups of users would be most interested in the activities: national security agencies, civilian government agencies, or private sector customers. The list of potential users is gathered from expressions of interest from conferences, the commercial space literature, current markets, and interviews. Likewise, for each potential activity, we provide a description of the technical or operational specifications a SpaaS provider may need to offer to meet a customer's needs.

c. Compare the Costs and Performance of Scenarios for Each Space Activity

For each space activity identified, we compare the utility and cost of the various SpaaS scenarios. We select the most appropriate outpost and alternative SpaaS scenarios to consider for comparison based on a rough matching of the customer's needs and the capabilities provided by the SpaaS scenarios. We generally provide a cost assessment of each chosen scenario, to illustrate which scenario is the most advantageous based on cost alone. However, some use cases may be more sensitive to mission requirements than cost, as is the case for some defense-related operations. For each space activity, we provide an assessment of the potential market for orbital outposts that incorporates the cost analysis and a discussion of the potential operational benefits.

4. Discussion of Cost Calculations for SpaaS Scenarios

We estimate the cost of each SpaaS scenario by tallying up the costs of a few major hardware systems. Specifically, we focus on the costs associated with the spacecraft bus and standard subsystems, robotic arms, RPO capabilities, and a small number of pieces of equipment that might be used onboard the spacecraft. Where possible, we provide a low and high-cost estimate for each hardware system. We also add a small additional cost for "payload adaption," which allows for sufficient satellite modularity to integrate the payload on orbit. Table 2 summarizes the cost estimates of the various hardware systems that we use to estimate the cost of each SpaaS scenario. Appendix A provides the justification for each hardware system.

Using a small set of common hardware systems to assemble each SpaaS scenario, we ensure an apples-to-apples comparison between the scenarios. For instance, all spacecraft in this report that require a large bus, including some orbital outposts, are assumed to use the SSL 1300 bus. In a later portion of the report, we provide a case study regarding the use of an orbital outpost as a replacement for the GOES-R satellites. In reality, the GOES-R satellites use the LM-A2100 bus, which does not cost the same as the SSL 1300. However, for this analysis, we estimate the hardware costs of a GOES-R satellite assuming that it does use the SSL 1300. This allows for an even comparison between the various scenarios.

Table 2. Costs and Masses of Hardware Systems Used to Calculate SpaaS Scenario Costs

Hardware System	Wet Mass [kg]	Low Cost [$M]	High Cost [$M]
Satellite Bus - Small	150	$5	-
Satellite Bus - Large	4,700	$125	-
Cargo Capsule	-	$160	$200
Traditional ISS-style Module	23,100	$570	$798
Robotic Arm - External	75	$15	$60
Robotic Arm - Internal	50	$15	$60
RPO Capability	0	$20	$60
Equipment - Microgravity R&D	100	$5	-
Equipment - Small Science Instrument	50	$20	-
Equipment - Large Science Instrument	175	$250	-
Payload Adaption	0	$5	$5

Some of the hardware systems have an operational lifetime that is too short to satisfy some of the requirements of the scenarios. For instance, the Dragon and Cygnus cargo capsules have operational lifetimes of approximately 2 years, while an orbital outpost would likely operate for approximately 10 years. To address this issue, we use a heuristic of doubling the cost of the hardware in question to bring its total operational lifetime to 10 years. Our basis for this heuristic comes from seeing hardware costs approximately double in the QuickCost model as the operational lifetime extends from 2 to 10 years.

In addition to costs of the hardware, we also tally up the estimated mass of the hardware required for each SpaaS scenario. The total mass is used to calculate the cost of launching the space vehicle into its operational orbit.[3] Adding these costs together yields the total hardware and launch costs that an outpost owner must recoup. Rather than making simple point-estimates for the hardware costs of each scenario, we use our low and high estimates to assemble a range of potential costs. All of our costs for future capabilities are estimated roughly. Our cost models are contained in a spreadsheet that is available to readers upon request so that they may substitute their own assumptions about space transportation costs into the analysis.

One economic argument for an outpost is that the cost of the bus and the robotic arms can be distributed over many potential users. These costs manifest themselves as one aspect of the rent that the outpost needs to charge the payload owner to cover their costs—other aspects are the amortization of the development costs and other costs that we are not calculating. The rent a customer pays is *in addition to* the cost of transportation to the outpost. As such, this cost is only present in SpaaS scenarios that use an orbital outpost.

To estimate potential rents for each outpost scenario, we posit a low and high estimate of simultaneous customers and use those estimates to calculate low and high rent values by amortizing the total hardware and launch costs over the assumed number of users. An outpost may not always be at full capacity; thus, our rents are calculated on a monthly basis, assuming various levels of customer usage over the entire lifetime of the outpost platform. We note that the costs per customer for outpost scenarios are more sensitive to our assumptions about customer usage than any other parameter. As such, uncertainties or errors related to our hardware cost estimates are generally not significant in comparison to the uncertainties related to customer usage.

D. Limitations of Our Approach

Our approach prioritizes the ability to analyze a broad landscape of space utilization, making apples-to-apples comparisons as much as possible. This requires a number of compromises to simplify the problem. For instance, we calculate launch costs per kilogram to LEO as effectively a single number. The cost to launch into LEO varies widely based on the launch location, launch vehicle, destination orbit, and whether the payload is a primary or secondary passenger. Likewise, we omit many costs from our estimates and must make our final assessments of cost competitiveness based on only a subset of the total costs. Including these details would introduce complexity that we believe would not change our assessment of the landscape; regardless, without performing a higher fidelity analysis, we cannot be sure.

Furthermore, we could not look at all possible SpaaS scenarios, potential space activities, or combinations of scenarios and activities. We attempt to be as comprehensive

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[3] Appendix A provides estimates for the various launch costs used throughout this document.

as possible, but we could not be exhaustive. For some potential space activities, we are simply unable to analyze them. For those we do analyze, we definitely do not capture all of the subtleties and nuances associated with the use of the SpaaS scenarios or the technical specifications required to perform the potential space activities. For example, the technical challenges associated with providing thermal management to modular payloads may be very challenging and we do not attempt to characterize the thermal needs of payloads or the thermal management services of SpaaS providers. Similarly, we do not rigorously address technical requirements for pointing accuracy, power generation, microgravity levels, communications, etc. We also do not address the scheduling complexities associated with attempting to satisfy many different customers on a single platform. Incorporating these details, while important, quickly produces a complex matching problem that leads to a geometric growth in the number of SpaaS scenarios to consider. To keep the problem tractable, we address these issues somewhat qualitatively and assume that for the bulk of customers, these issues are not the main decisive factor in their decision making.

One class of alternative scenarios is largely missing from our analysis: the ability to perform the space activity in terrestrial facilities. For instance, when performing development testing of a spacecraft, companies and Federal agencies have substantial infrastructure for ground-testing space systems. Similar situations arise regarding microgravity R&D, space situational awareness, and orbital debris removal. All of these missions have the potential for terrestrial capabilities to provide adequate services that may compete with in-space platforms. An analysis that compares terrestrial infrastructure to space platforms would be substantially different from an analysis that simply compares space platforms with each other. As such, we make the simplifying assumption that customers truly require long-duration access to space to accomplish their mission.

In an effort to set a level field for comparisons across outposts with all alternatives, our analysis focuses on robotic outposts only. Making an outpost capable of human occupancy is expensive. Many of the proposed concepts do not envision human occupancy, so comparing outposts designed for human occupancy with those that are not may be misleading. If one assumes that some outposts are capable of hosting humans, we initially suspected that these outposts would be unlikely to outcompete purely robotic alternatives. In retrospect, we see multiple avenues by which this assumption may not be true. We provide a discussion of the potential for crewed in-space platforms in the conclusion; however, we do not analyze them in depth.

E. Organization of This report

We first describe potential SpaaS scenarios using orbital outposts and alternatives to outposts in Chapter 2. There is substantial overlap between the hardware used among all of the scenarios; details regarding the estimated costs and performance of the hardware systems used in Chapter 2 are provided in Appendix A. Each section in Chapter 3 analyzes a different category of space activities for which an outpost might provide utility. For each category of activity, we generally analyze a few possible instantiations of the activity. Finally, Chapter 4 provides an overall assessment of the viability of orbital outposts, the effect that trends in the space industry may have on our viability assessment, and recommendations for the U.S. Government regarding how to develop orbital outpost capabilities.

2. Scenarios for Orbital Outposts and Alternatives

In this chapter, we illustrate a range of scenarios that provide SpaaS. First, we discuss in greater depth what is and is not an orbital outpost. Next, we discuss scenarios that use orbital outposts and estimate a range of costs associated with each. A significant differentiator between these scenarios is the buses used. The building block outpost scenarios use a small satellite bus, while the condo satellite outpost scenarios use a large satellite bus. These scenarios are appropriate for hosting payloads that do not require pressurized volume. We provide scenarios for capsule outposts and traditional module outposts, which use cargo capsules and ISS-like modules for their buses, respectively. These outpost scenarios are appropriate for hosting payloads that require pressurized volume.

Finally, we provide other scenarios for providing SpaaS against which outpost operators will compete for customers. Specifically, we describe scenarios where payloads are hosted on a disposable orbital transfer vehicle (d-OTV), a reusable orbital transfer vehicle (r-OTV), or a reusable cargo capsule.[4] We label these scenarios as alternative scenarios—or simply "alternatives." These alternatives may be a preferable method of space access compared to the outpost scenarios.

As discussed in our methodology section, we do not include the development and operations costs associated with the use of the outposts and alternatives in our estimates below. This simplifies the analysis by removing many degrees of freedom, while likely preserving the relative competitiveness of each scenario. However, it also means that the costs below are likely to be underestimates of the true costs; they should not be used out of the context of this comparative analysis.

A. Outpost Scenarios

As previously described, we define an orbital outpost for this study as a persistent, uncrewed platform in space capable of hot-swapping5 payloads on orbit. In the subsections that follow, we provide outpost scenarios of our own creation that meet this definition. We

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[4] See Appendix A for a discussion of d-OTVs and r-OTVs.

[5] In this context, hot swapping is the addition or replacement of components on a space vehicle while the vehicle is operational. The process can be performed without interrupting the vehicle's operation.

note that DIU awarded study contracts to three potential providers of orbital outpost services: Nanoracks, Arkisys, and Sierra Nevada.[6] Our scenarios are partially informed by conversations with representative from these companies, but we have not made an effort to substantially recreate their potential designs. If our outpost scenarios were too closely aligned with the proposals of these companies, then our study would lack the generality required to understand the broader landscape for orbital outposts. As such, the scenarios that follow also incorporate insights from various subject matter experts whom we interviewed and concepts from the literature. While not fully comprehensive, we believe our scenarios reasonably span the range of potential possibilities for an orbital outpost from the perspective of costs and capabilities delivered to customers.

In all scenarios we consider, we assume that a payload attached to an outpost cannot simply be jettisoned when its mission ends. While this approach has been used for some external payloads on the ISS, it likely becomes infeasible for altitudes higher than 400km. The outpost's orbit would become somewhat cluttered with junk. Likewise, by actively de-orbiting the payloads, orbital debris and post-mission disposal regulations will be more likely satisfied. Passive measures for debris removal, such as tethers or drag sails could be employed, but their deployment near an outpost may put the outpost in some amount of danger. Also, their use may increase the lifetime probability of collision associated with the object, leading to an unacceptable solution. Active disposal of the payloads is likely the most preferred option.

1. Building Block Outpost

The building block outpost is designed to be a highly modular system, both with its payloads as well as with its own infrastructure. The initial elements of the outpost can range in size from dozens to hundreds of kilograms. The basic idea is that new parts of the outpost can be launched and connected to the existing system to provide additional capacity, capabilities, and services. Interfaces between similar modules can exchange power, data, and fluids as necessary. The outpost can be expanded with new hardware attached to those interfaces.

New additions to the outpost can be nearly any size, though to save on development costs they would likely be similar to the first iteration of the outpost. Pieces of the outpost can be reconfigured and repositioned into many different shapes and structures as more elements are launched over time. Figure 4 illustrates how a building block outpost can grow and be reconfigured over time. In this section, we provide costs for two scenarios of building block outposts.

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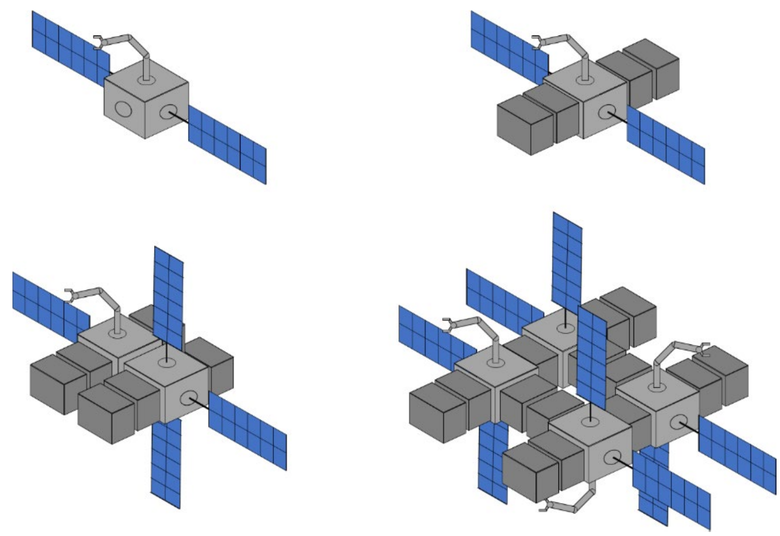
[6] Searching for the term "orbital outpost" in DACIS yields the following contracts: Nanoracks, Contract #HQ00342090004; Arkisys, Contract #HQ00342090015; Sierra Nevada, Contract #HQ00342090011;



Showing: (top left) single building block element, (top right) element with payloads in series, (bottom left), paired building blocks with payloads, and (bottom right) multiple elements and multiple payloads. Credit: Benjamin Corbin, STPI.

Figure 4. Illustration of Potential Modularity of a Building Block Outpost

a. RPO-Capable Building Block

In this scenario, the outpost has RPO capabilities and arms, allowing it to be visited by d-OTVs and to self-assemble with new building block modules if necessary. A single building block is assumed to consist of a modified Blue Canyon X-Sat bus, a single robot arm, and requires modifications for payload adaptation. Figure 5 illustrates the CONOPS for this scenario.

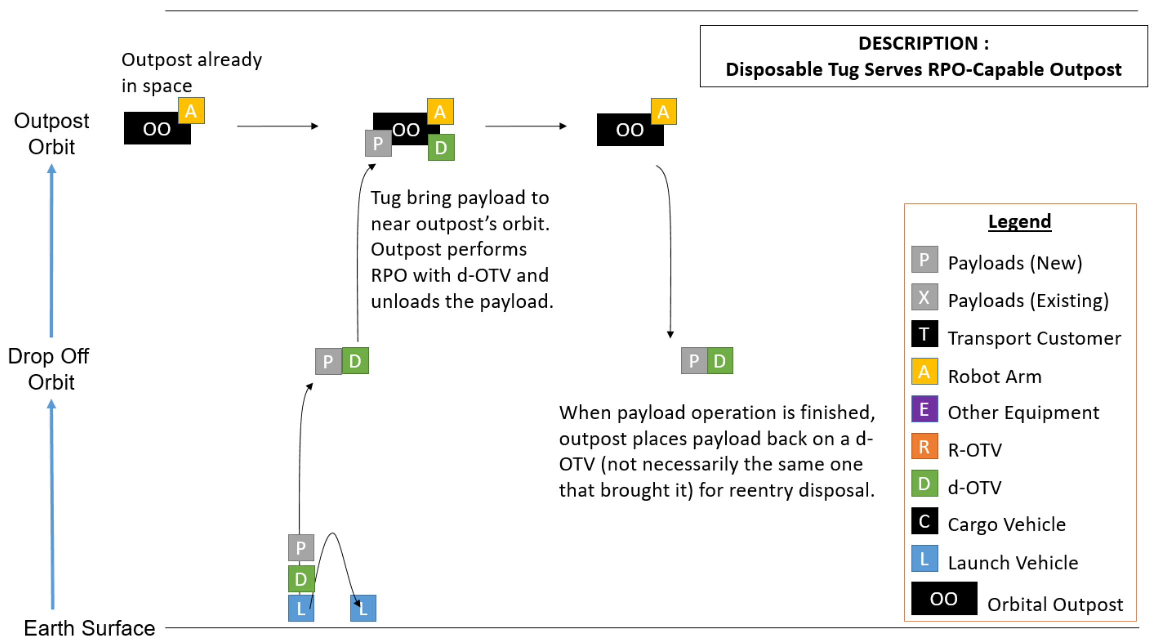


Figure 5. CONOPS for an RPO-Capable Building Block Outpost

The costs associated with building and launching the outpost—but excluding development and operations costs—are shown in Table 3. For situations where the outpost is delivered to GEO, it is launched to a geosynchronous transfer orbit (GTO), along with a d-OTV that delivers it to its final orbit. See Appendix A for details on the cost estimates associated with these launch capabilities.

Table 3. Cost of Hardware and Launch for RPO-Capable Building Block Outpost

Element	Units	Low Cost [$k]	Low Mass [kg]	High Cost [$k]	High Mass [kg]
Bus (X-Sat)	1	5,000	150	5,000	150
Life Extension	0	-	-	-	-
Arm External	1	15,000	75	60,000	75
Payload Adaption	1	5,000	0	5,000	0
RPO Capability	1	20,000	0	60,000	0
SubTotal		**45,000**	**225**	**130,000**	**225**
Launch to LEO ($5k/kg)		1,125		1,125	
Total to LEO[a]		**46,000**		**130,000**	
Launch to GTO ($15k/kg)		3,375		3,375	
GTO to GEO ($15-40k/kg)		3,375		9,000	
Total to GEO[a]		**52,000**		**140,000**	

Note: As development and operations costs have been excluded, an outpost operator's full costs will likely be more than this amount.

[a] Rounded to two digits.

We assume that a single building block can host six customers simultaneously. With an orbital lifetime of 120 months, that leads to a total utilization time of 720 customer-months. For this analysis, we estimate a range of monthly rents based on full usage and half usage (360 customer-months), shown in Table 4. These costs exclude the launch of the payload and the costs of any specialized test equipment that may be present on the outpost. The outpost provider must charge at least this much rent to cover the costs of the hardware and launch.

Table 4. Representative Monthly Rents for an RPO-Capable Building Block Outpost

	LEO		GEO	
	Low Cost [$k][a]	High Cost [$k][b]	Low Cost [$k][c]	High Cost [$k][d]
Max Usage	65	180	70	190
Half Usage	130	360	140	390

Note: All numbers rounded to 1 or 2 digits.

[a] Low-cost outpost in LEO ($46 million) divided by max (720) or half (360) number of customer-months.

[b] High-cost outpost in LEO ($130 million) divided by max (720) or half (360) number of customer-months.

[c] Low-cost outpost in GEO ($52 million) divided by max (720) or half (360) number of customer-months.

[d] High-cost outpost in GEO ($140 million) divided by max (720) or half (360) number of customer-months.

These rent costs are appropriate for use with a d-OTV to deliver payloads to the outpost. In this case, the d-OTV co-orbits with the outpost as best it can, then turns off its control systems, allowing it to be captured and manipulated by the RPO-capable outpost. An RPO-capable building block could also be serviced by an r-OTV; however, that would be unnecessarily expensive. For our analysis, we only consider a visiting d-OTV.

b. Stripped Down Building Block

The second scenario removes RPO capabilities and arms, providing the cost of a stripped down building block. If flown on its own, the stripped down building block would need to be visited by a satellite-servicing vehicle for payload or satellite reconfiguration. Alternatively, a stripped down building block would be the least-cost addition to a multi-element building block architecture. Figure 6 illustrates the CONOPS for this scenario.

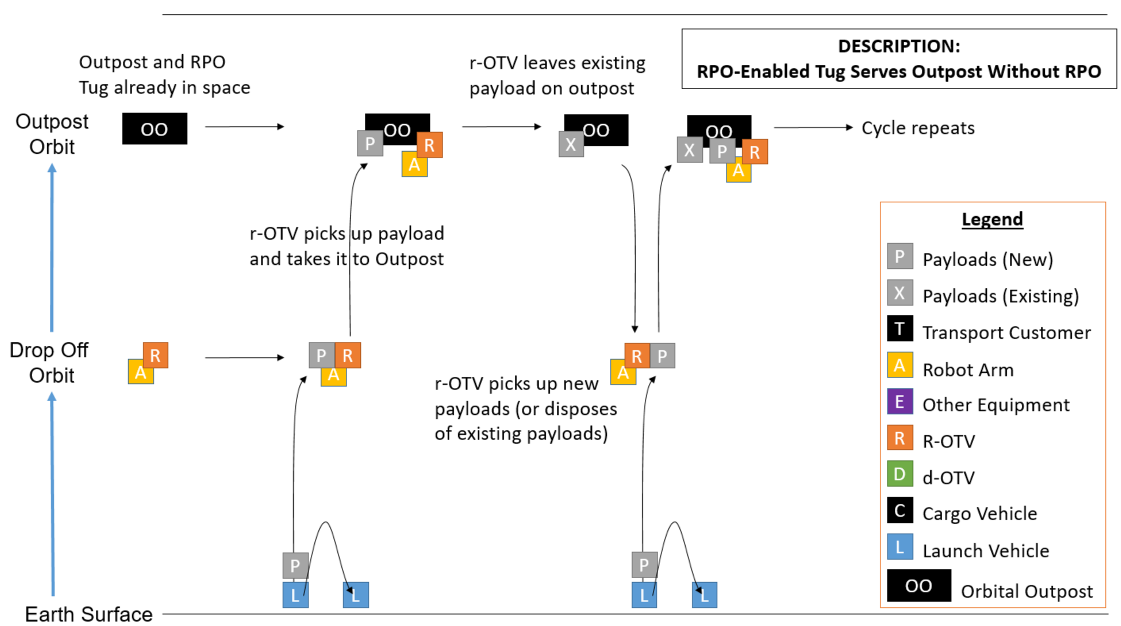


Figure 6. CONOPS for a Stripped Down Building Block Outpost

The costs associated with building and launching the outpost are shown in Table 5. We use the same assumptions as the previous building block scenario, except that we remove the arm and the RPO capability. In this scenario, the high and low-cost estimates for the hardware are degenerate due to the omission of robotic arms and RPO capabilities. Likewise, there is not a substantial cost between LEO and GEO orbits, because the outpost is relatively low mass.

Table 5. Cost of Hardware for Stripped Down Building Block Outpost

Element	Units	Low Cost [$k]	Low Mass [kg]	High Cost [$k]	High Mass [kg]
Bus (X-Sat)	1	5,000	150	5,000	150
Life Extension	0	-	-	-	-
Arm External	0	-	-	-	-
Payload Adaption	1	5,000	0	5,000	0
RPO Capability	0	-	-	-	-
SubTotal		**10,000**	**150**	**10,000**	**150**
Launch to LEO ($5k/kg)		750		750	
Total to LEO[a]		**11,000**		**11,000**	
Launch to GTO ($15k/kg)		2,250		2,250	
GTO to GEO ($15-40k/kg)		2,250		6,000	
Total to GEO[a]		**15,000**		**18,000**	

Note: As development and operations costs have been excluded, an outpost operator's full costs will likely be more than this amount.

[a]. Rounded to two digits.

As with the previous scenario, we assume that a single building block can host six customers simultaneously. We estimate a range of rents the outpost operator would charge at full and half capacity over the lifetime of the outpost, shown in Table 6. The outpost provider must charge at least this rent to cover the costs of the hardware and launch.

Table 6. Representative Monthly Rents for a Stripped Down Building Block Outpost

	LEO		GEO	
	Low Cost [$k][a]	High Cost [$k][a]	Low Cost [$k][b]	High Cost [$k][c]
Max Usage	15	15	20	25
Half Usage	30	30	40	50

Note: All numbers rounded to 1 or 2 digits.

a. Outpost in LEO ($11 million) divided by max (720) or half (360) number of customer-months.

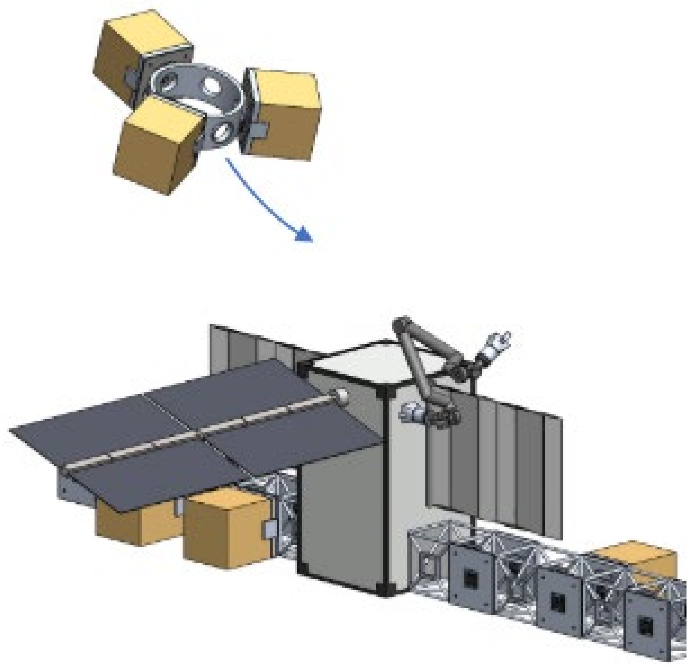
b. Low-cost outpost in GEO ($15 million) divided by max (720) or half (360) number of customer-months.

c. High-cost outpost in GEO ($18 million) divided by max (720) or half (360) number of customer-months.

The vehicle that delivers the payload must have RPO capability to approach this outpost, which lacks RPO capabilities. Using the same demand assumptions as before, we calculate the monthly rent associated with this case in Table 6. Alternatively, if this stripped down module is added to a previously flown RPO-capable building block, then the rent costs associated with this module would be added to the rent costs of the previously flown module.

2. Condo Satellite Outpost

The condo satellite outpost is the most similar to existing satellite systems. This outpost is essentially a standard satellite bus with slots for modular payloads that are capable of being swapped on orbit. Mukherjee et al. (2020) proposes a system that distributes the payloads along a truss structure, so that all payloads can easily point toward the Earth for remote sensing measurements. Figure 7 shows an illustration of such an outpost. Swapping payloads can be done with a robotic arm that is either installed on the outpost or provided by the cargo delivery service. There is no internal volume to host payloads or provide a habitable environment.



Source: Mukherjee et al. 2020

Figure 7. Illustration of a Potential Condo Satellite Outpost

In general, a condo satellite could be large or small. For the sake of analysis, we consider a single unit of the building block outpost as reasonably covering small, unpressurized outposts; thus, for the condo satellite we use a GEO bus. We provide costs for two scenarios of CondoSat. The first scenario assumes that payloads will be swapped in and out frequently, while the second scenario assumes that payloads are only swapped when a technology refresh is required.

a. High Traffic CondoSat

In this scenario, many different tenants will use the outpost for potentially short periods of time; hence, the name "high traffic." The outpost will require RPO capabilities to maximize the ability for payloads to ride on any vehicle to reach to the outpost. In this manner, the CONOPS is effectively the same as shown in Figure 5; however, this outpost is larger and will have two robotic arms.

The core of the outpost is assumed to be based on the SSL 1300 bus. In addition to the RPO capabilities mentioned, it contains two robotic arms. The mass of the outpost is greater than our reference d-OTV can tug; thus, for launches to GEO, we use a launch cost for going directly to GEO. See Appendix A for more details on this launch cost. The hardware and launch costs for this scenario are shown in Table 7.

Table 7. Cost of Hardware for High Traffic CondoSat Outpost

Element	Units	Low Cost [$k]	Low Mass [kg]	High Cost [$k]	High Mass [kg]
Bus (SSL 1300)	1	125,000	4,700	125,000	4,700
Life Extension	0	-	-	-	-
Arm External	2	30,000	150	120,000	150
Payload Adaption	1	5,000	0	5,000	0
RPO Capability	1	20,000	0	60,000	0
SubTotal		180,000	4,850	310,000	4,850
Launch to LEO		24,250		24,250	
Total to LEO[a]		200,000 [b]		330,000	
Launch to GEO ($40k/kg)		194,000		194,000	
Total to GEO[a]		370,000 [b]		500,000	

[a] Rounded to two digits.

[b] As development and operations costs have been excluded, an outpost operator's full costs will likely be more than this amount.

We assume that a single CondoSat can host 12 customers simultaneously. With an orbital lifetime of 120 months, that leads to a total utilization time of 1440 customer-months. For this analysis, we estimate a range of monthly rents based on full usage and half usage (720 customer-months), shown in Table 8. These costs exclude the launch of the payload and the costs of any specialized test equipment that may be present on the outpost. These rents are only appropriate for use with an r-OTV that can bring the payload to the outpost.

Table 8. Representative Monthly Rents for a High Traffic CondoSat Outpost

	LEO		GEO	
	Low Cost [$k][a]	**High Cost [$k] [b]**	**Low Cost [$k] [c]**	**High Cost [$k] [d]**
Max Usage	140	230	260	350
Half Usage	280	460	510	690

Note: All costs rounded to two digits.

[a] Low-cost outpost in LEO ($200 million) divided by max (1440) or half (720) number of customer-months.

[b] High-cost outpost in LEO ($330 million) divided by max (1440) or half (720) number of customer-months.

[c] Low-cost outpost in GEO ($370 million) divided by max (1440) or half (720) number of customer-months.

[d] High-cost outpost in GEO ($500 million) divided by max (1440) or half (720) number of customer-months.

b. Technology Refresh CondoSat

Alternatively, a CondoSat could be owned and operated by a single user (e.g., The National Oceanic and Atmospheric Administration [NOAA]) in a manner similar to a traditional satellite. The value of using a CondoSat rather than a traditionally integrated satellite is that if one of the instruments fails, it can be replaced on orbit for only the cost of an additional sensor and delivery of the sensor to the outpost. The CONOPS for this scenario, shown in Figure 8, is similar to the previous CONOPS for the stripped-down building block. The primary difference here is that this bus provides far more power to payloads and that the modularity is not meant to be used under nominal operations.

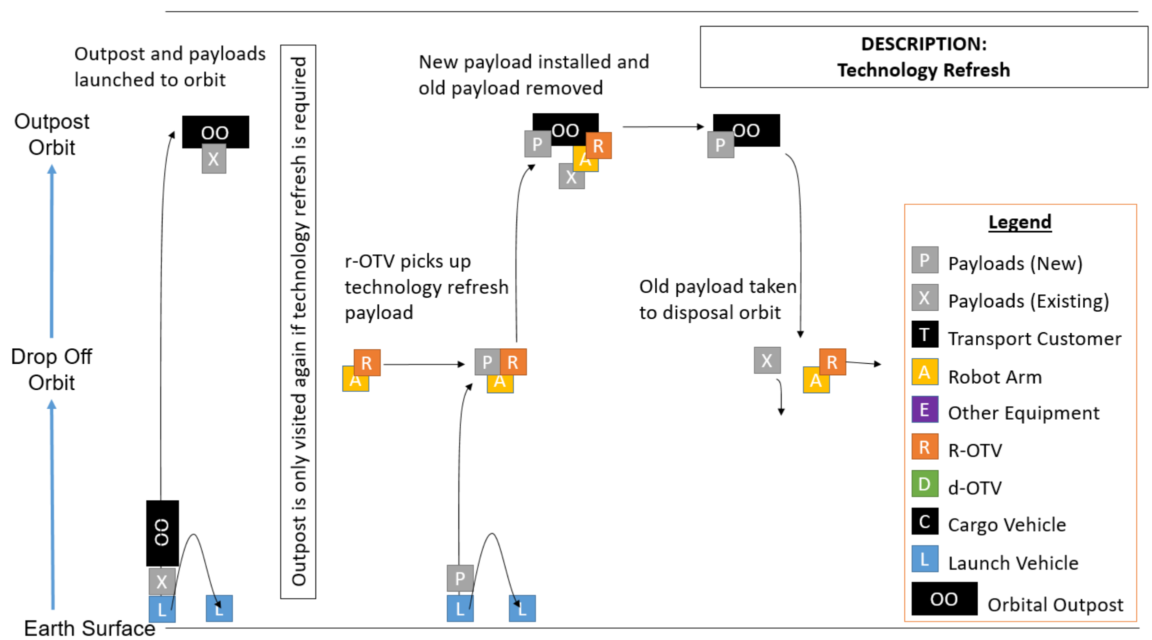


Figure 8. CONOPS for a Technology Refresh CondoSat Outpost

Similar to the stripped down building block, this scenario removes the RPO and robotic manipulation capabilities. Costs associated with this scenario are shown in Table 9. The primary benefit of this CondoSat scenario is the ability to reduce the downside risk of instrument failure. In the nominal use case—where no payloads fail—no payloads would ever be replaced. This CondoSat owner can forego the costs of RPO capabilities and robotic arms, opting to pay a premium for their use only if absolutely necessary; in which case, they would likely be resident on an r-OTV. This scenario could be used to reduce the risks associated with flying payloads by being more tolerant to instrument failures.

Table 9. Cost of Hardware for CondoSat Technology Refresh

Element	Units	Low Cost [$k]	Low Mass [kg]	High Cost [$k]	High Mass [kg]
Bus (SSL 1300)	1	125,000	4,700	125,000	4,700
Life Extension	0	-	-	-	-
Arm External	0	-	-	-	-
Payload Adaption	1	5,000	0	5,000	0
RPO Capability	0	-	-	-	-
SubTotal		130,000	4,700	130,000	4,700
Launch to LEO		23,500		23,500	
Total to LEO[a]		150,000		150,000	
Launch to GEO ($40k/kg)		188,000		188,000	
Total to GEO[a]		320,000		320,000	

[a.] Rounded to two digits.

In this scenario, rents are not meaningful as the owner of the CondoSat will pay the full cost of the outpost. Since there is only one customer, an effective rent might be the annualized cost of the outpost's hardware and launch costs. However, for the remainder of our analysis, we use the full costs from Table 9.

3. Capsule Outpost

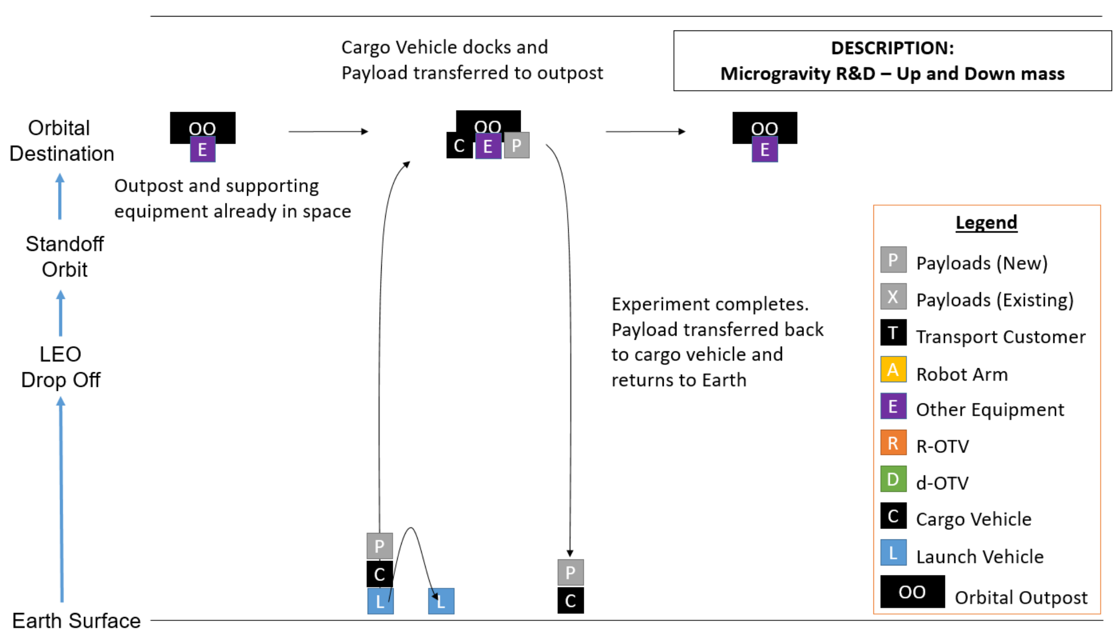


Figure 9. Concept of Operations for a Microgravity R&D Outpost

For an outpost based on a currently operational cargo capsule, we use Northrop Grumman's Cygnus capsule as the base design for a low-cost option. [7] This is preferred over the SpaceX Dragon capsule because Cygnus has greater payload volume, reduced unit cost, and Earth-return capabilities not embedded in the cost. The Cygnus has a relatively short orbital lifetime, thus we include the cost of a life extension for the outpost. The outpost is assumed to have two robotic arms, one internal and one external. Cygnus has RPO capabilities, but the outpost does not need this capability, as the primary vehicles that visit the outpost will be cargo vehicles with their own RPO capabilities. As such, we subtract the costs associated with RPO from the Cygnus costs. For a high-cost option, we replace the cost of Cygnus with the estimated cost of the Dragon cargo capsule, but hold all other assumptions the same as in the low-cost option.

a. Microgravity R&D Facility

The CONOPS for this scenario is essentially the same as the stripped-down building block, except that now the in-space transportation vehicle is a pressurized cargo vehicle instead of an r-OTV. Additionally, the outpost has on board a suite of equipment for hosting microgravity R&D experiments. We make the simplifying assumption that this outpost will use something like the EXPRESS racks on the ISS to host experiments.[8] Further, we optimistically assume that any specialized instruments required for on-orbit experimentation (e.g., video cameras for watching fluid dynamics experiments) are contained in the mass and cost we have assumed for the EXPRESS rack.

Each EXPRESS rack takes 1.6 cubic meters of volume; thus, approximately 16 racks could fit inside the Cygnus's 27 cubic meters of pressurized volume. To allow for arm volume and space to maneuver payloads inside the station, we remove 1 EXPRESS rack, for a total of 15 racks. These 15 racks will provide 135 Middeck Locker Equivalents (MLEs) of volume for hosting experiments.[9] There are 3 cubic meters left available for the internal robotic arm to maneuver. Table 10 provides the costs associated with the hardware and launch costs for this scenario. We see no need for such a facility in GEO or other orbits; thus, we only consider their use in LEO.

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7 Originally developed by Orbital Sciences, but now owned by Northrop Grumman, the Cygnus capsule regularly carries supplies to the ISS. It is disposable and cannot return mass to Earth. See Appendix A for more details.

8 See the section on microgravity R&D equipment in Appendix A for a discussion of EXPRESS racks. They are a piece of infrastructure that manages power, communications, etc. for hosted experiments.

9 See the section on microgravity R&D equipment in Appendix A for a discussion of middeck lockers. They are containers that can hold experiments. Each locker is about the size of a large microwave oven.

Table 10. Cost of Hardware and Launch for Microgravity R&D Outpost

Element	Units	Low Cost [$k]	Low Mass [kg]	High Cost [$k]	High Mass [kg]
Cygnus & Dragon	1	160,000	4,600	200,000	5,800
Life Extension	1	160,000	-	200,000	-
Arm Internal	1	15,000	50	60,000	50
Arm External	1	15,000	75	60,000	75
Payload Adaption	1	5,000	-	5,000	-
RPO Capability	-1	-20,000	-	-20,000	-
EXPRESS Rack	15	75,000	1,500	75,000	1,500
SubTotal		410,000	6,225	580,000	7,425
Launch to LEO ($5k/kg)		31,125		37,125	
Total to LEO[a]		440,000 [b]		620,000	

[a.] Rounded to two digits.

[b.] As development and operations costs have been excluded, an outpost operator's full costs will likely be more than this amount.

The maximum number of simultaneous customers that can be hosted on an outpost is related to the maximum number of EXPRESS racks that fit inside the outpost. We provide rent estimates for two different volumes of experiments. For the first, we assume that each customer will use one MLE on average. With an orbital lifetime of 10 years and 135 customers, that leads to a total utilization time of 16,200 customer-months.[10] For this analysis, we estimate a range of monthly rents based on full usage, half usage (8,100 customer-months), and quarter usage (4050 customer-months). As will be discussed later, even quarter capacity—about 34 simultaneous users—is somewhat optimistic compared to the usage we see today on the heavily subsidized ISS platform. Table 11 summarizes the cost per customer-month, which is identical to the cost to rent one MLE of volume for 1 month, for the low and high-cost scenarios. These costs exclude the launch of the payload and the costs of any other specialized test equipment that may be present on the outpost.

[10] 135 customers * 10 years * 12 months per year

Table 11. Representative Monthly Rents for a Microgravity R&D Outpost

	Cost per MLE per month [$k]		Cost per U per month [$k]	
	Low[a]	High[b]	Low[c]	High[d]
Max Usage	$27	$38	$1.1	$1.6
Half Usage	$54	$77	$2.3	$3.2
Quarter Usage	$110	$150	$4.5	$6.4

a. Total cost of low-cost outpost from Table 10 divided by the appropriate number of customer-months.

b. Total cost of high-cost outpost from Table 10 divided by the appropriate number of customer-months.

c. Low cost per MLE divided by 24

d. High cost per MLE divided by 24

To perform R&D on the outpost, many experiments are likely to be containerized to fit inside of a CubeSat form factor, commonly measured in units of U.[11] Appendix A discusses the technical specifications for a CubeLab, which allows 24 U of experiments to be hosted in a single MLE. In this case, an outpost could potentially host up to 3,240 U of experiments simultaneously.[12] Table 11 also provides representative monthly rents on a per-U basis. We perform our subsequent analysis of microgravity R&D activities on a per-U basis.

To transport the payloads to the outpost, we use the cargo Dragon because it allows for docking with the outpost to deliver pressurized payloads and allows for mass to be returned to Earth. When used to deliver pressurized payloads, the Dragon can accommodate 1,650 U of experiments.[13] The hardware and launch costs are approximately $90 million per mission. Table 12 shows the representative costs per U associated with transporting a full or quarter load of microgravity experiments to the outpost.

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11 One U is a cube, 10 centimeters on each side, with a mass no greater than 1.3 kg. It is the standard unit for measuring CubeSats.

12 135 MLE * 24 U per MLE

13 Dragon's pressurized up-mass is 3,300 kg. Each U of experiment has a mass of 1.3 kg and requires about 0.7 kg more mass for its storage and deployment mechanisms—that is, 2 kg of mass total to send a single U of experiment to space in the capsule.

Table 12. Representative Cost to Transport Microgravity Payloads to the Outpost

Element	Num Units	Unit Cost ($M)	Total Cost ($M)
Falcon 9 Launch	5	50[a]	250
Dragon	1[b]	200	200
Total			**450**
Cost per Mission			**90**

Usage Rate	Cost per U ($k)[c]
Max	55
Half	110
Quarter	220

[a] Launch is $50 million, but only half of the payload mass is available for microgravity experiments. We assume that SpaceX effectively fills the trunk section; thus, other customers pay for the other half of the launch.

[b] A single Dragon can be used 5 times.

[c] Cost per Dragon launch ($90 million) divided by appropriate fraction of 1,650 U.

b. Production Facility for Serving Terrestrial Markets

For this type of outpost, the CONOPS is similar to the microgravity R&D facility, except that the entire internal volume is utilized by a single user for mass manufacturing of goods, such as ZBLAN or silicon carbide. This single user may purchase and operate the entire facility, allowing it to be optimized for production throughput, or rent the facility for months at a time. The payloads sent to the outpost are preform or other material inputs needed for the manufacturing process. The cargo vehicle that delivers the inputs will also return the goods to customers on Earth. We assume that the user renting the production facility will bring their own equipment. Such costs will be incorporated in the analysis of activities in the following chapter. Table 13 shows the representative costs for the high and low-cost options.

Table 13. Cost of Hardware and Launch for Microgravity Production Facility Outpost

Element	Units	Low Cost [$k]	Low Mass [kg]	High Cost [$k]	High Mass [kg]
Cygnus & Dragon	1	160,000	4,600	200,000	5,800
Life Extension	1	160,000	-	200,000	-
Arm Internal	1	15,000	50	60,000	50
Arm External	1	15,000	75	60,000	75
Payload Adaption	1	5,000	-	5,000	-
RPO Capability	-1	-20,000	-	-20,000	-
SubTotal		**335,000**	**4,725**	**505,000**	**5,925**

Element	Units	Low Cost [$k]	Low Mass [kg]	High Cost [$k]	High Mass [kg]
Launch to LEO ($5k/kg)		23,625		29,625	
Total to LEO[a]		**360,000[b]**		**530,000**	

a. Rounded to two digits.

b. As development and operations costs have been excluded, an outpost operator's full costs will likely be more than this amount.

Most likely, a single user will purchase and operate the entire facility, allowing it to be optimized for production throughput. As such, there is no rent to charge. However, we calculate monthly rent values for a single user to facilitate comparisons with other outpost scenarios, shown in Table 14.

Table 14. Representative Monthly Rents for a Microgravity Production Facility Outpost

	Low Cost [$k][a]	High Cost [$k][b]
Single User	$3,000	$4,500

a. Total cost of low-cost outpost from Table X divided by the 120 months of lifetime operations.

b. Total cost of low-cost outpost from Table X divided by the 120 months of lifetime operations.

4. Traditional Module Outpost

The traditional module outpost builds on the heritage of the components of the ISS and the systems under development to succeed the ISS. Unlike the ISS, a traditional module outpost would have highly capable robotic systems to do all the internal work without the presence of a crew.

As described in Appendix A, we assume a standardized volume of 330 cubic meters for both the low and high-cost options; this was the proposed volume of the Bigelow 330 (B330) module, which is about twice the volume of the modules currently on the ISS. We note that the launch operations for a large expandable module, such as the B330, would be substantially different from a rigid module. Specifically, a rigid module can be flown with all of the internal lab equipment pre-installed inside the module, while an expandable module would need the lab equipment to be installed—and possibly launched—separately. For simplicity, we do not attempt to account for this effect in our estimation of the hardware and launch costs.

We assume that the internal volume will be used for both microgravity R&D and for production facilities. This mixed usage is unlikely for a smaller outpost, such as a capsule outpost, but is likely for a module outpost, which has approximately 12 times more internal volume than the capsule outpost. We assign 1/12 of the internal volume to the R&D portion of the outpost; this provides the same amount of internal volume as the capsule outpost. The production facilities are assigned the remaining 11/12 of the volume. We assign four robotic arms to the internal volume to tend to the R&D and production users. A single robotic arm is placed outside to facilitate payloads attached to the external volume. The costs of these elements are spread across all users and are considered the base costs in Table 15.

For the R&D facilities, we assign 1/12 of the base cost—in line with its volumetric usage—and provide 15 EXPRESS Racks. This is the same as we assigned to the capsule module. Likewise, the number of simultaneous R&D customers is the same for the capsule and the module outpost. Rents for breaking even on hardware costs are provided in Table 16.

Table 15. Hardware and Launch Costs for a Traditional Module Outpost

Element	Units	Low Cost [$k]	Low Mass [kg]	High Cost [$k]	High Mass [kg]
Bus	1	570,000	23,100	798,000	36,100
Life Extension	0	-	-	-	-
Arm Internal	4	60,000	200	240,000	200
Arm External	1	15,000	75	60,000	75
Payload Adaption	1	5,000	-	5,000	-
RPO Capability	0	-	-	-	-
Subtotal Base		650,000	23,375	1,103,000	36,375
Launch to LEO ($5k/kg)		116,875		181,875	
Total Base		766,875		1,284,875	
Subtotal R&D[a]		63,906		107,072	
EXPRESS Racks	15	75,000	1,500	75,000	1,500
Launch to LEO ($5k/kg)		7,500		7,500	
Total for R&D		150,000		190,000	
Subtotal Production [b]		702,968		1,177,802	
Total for Production		700,000		1,200,000	

Note: Total for R&D and Total for Production are rounded to two digits.

[a.] We assume that 1/12 of the internal volume will be used for R&D. Thus, we allocate 1/12 of the total base cost to R&D customers.

[b.] The remaining 11/12 of the total base cost is assigned to production customers.

For the production facilities, we assign the remaining 11/12 of the base cost. We use the same assumptions as before with the capsule outpost, that the user will bring their own fabrication equipment. Rents for breaking even on hardware and launch costs in the production facility are provided in Table 16.

Table 16. Monthly Rent to Recoup Hardware and Launch Costs for Module Outpost in LEO

	R&D Cost per U per Month[a]		Production Cost per Month[b]	
	Low Cost [$k][c]	High Cost [$k][d]	Low Cost [$k][e]	High Cost [$k][f]
Max Usage	0.40	0.50	530	900
Half Usage	0.8	1.0	1,100	1,800
Quarter Usage	1.6	2.0	2,100	3,600

Note: Costs are rounded to 1 or 2 digits.

a. With 3,240 U of available space for customers, there may be 3,240 customers * 10 years * 12 months per year = 388,800 customer months at maximum.

b. There may be 11 simultaneous customers * 10 years * 12 months per year = 1,320 customer-months.

c. Total low cost for R&D ($150 million) divided by the appropriate number of customer-months.

d. Total high cost for R&D ($190 million) divided by the appropriate number of customer-months.

e. Total low cost for production ($700 million) divided by the appropriate number of customer-months.

f. Total high cost for production ($1,200 million) divided by the appropriate number of customer-months.

B. Alternative Scenarios

The orbital outpost scenarios described in the previous section are not the only way to provide access to space. Indeed, outpost scenarios may not be the fastest or cheapest method of space access for some space activities. In this section, we describe alternative scenarios for accessing space that do not rely on an outpost. For an outpost scenario to win customers, it must compare favorably with the alternative scenarios here.

1. Disposable Orbital Transfer Vehicle (d-OTV)

In this scenario, a launch vehicle lifts a disposable tug without RPO capabilities, possible transportation customers that only need their asset delivered to a specific orbit, and one or more payloads being provided with SpaaS. This scenario is appropriate for payloads that do not require pressurized volume or on-orbit periods greater than 1 year. As discussed previously, we take the price of the service to be between $6,000 and $24,000 per kilogram.

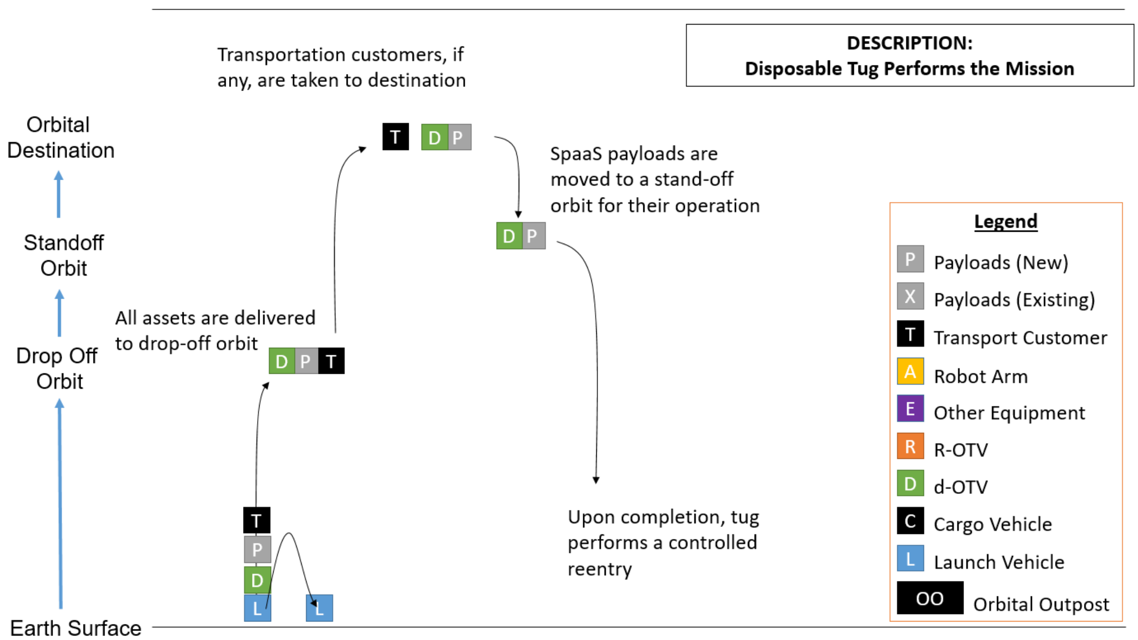

Figure 10. CONOPS for a d-OTV to Host the Payload

For simplicity, we neglect the cost of operations the tug may charge the payload. Unlike a persistent platform, for a single-use platform all of the unit costs and an appropriate amount of development costs are covered by the price of the transportation service. There is little incentive to charge the payload “rent” because the tug operator does not have the option to swap out the payload for a new paying customer. For this reason, it seems appropriate that for time durations up to 1 year, the cost of using a disposable tug is effectively independent of time. There will in fact be some level of operations required, such as for performing conjunction analysis and station keeping, that will entail time-based charges. However, this can be largely automated and we assume that the cost will not be so great that it substantially changes our relatively wide cost boundaries. If a payload needs to be kept alive for up to 10 years, we use the heuristic that the hardware cost of such a vehicle roughly doubles, as discussed in the methodology section of this report. Table 17 summarizes our calculations from Appendix A of the cost of using a d-OTV.

Table 17. Cost Associated With Launching and Hosting Payload on a D-OTV

	Cost to LEO ($k/kg)		Cost to GEO ($k/kg)	
Duration	**Low**	**High**	**Low**	**High**
Short	6	20	15	40
Extended	10	30	20	50

Note: See Appendix A for calculations

The hardware costs of the bus are already captured in the cost per kilogram associated with transportation using the disposable tug; there is no rent to charge because the tug does not have future potential customers over which to amortize costs. To the extent that the disposable tug does charge rent, the rent will reflect the operations costs associated with payload operation and we have already assumed that these operations costs are approximately the same as for the outpost.

2. Reusable Orbital Transfer Vehicle (r-OTV)

In this scenario, the r-OTV is already in space and travels to the drop-off orbit where it picks up its newly launched customers. In general, the customers may be a mix of those who simply want transportation services and those who want to be hosted for a short period of time. The r-OTV could deliver its transportation customers to their specified orbit and bring along a few SpaaS payloads that will be integrated and operated afterwards. When new transportation or SpaaS customers are delivered to LEO, the r-OTV can carry the old payloads to the drop-off orbit, detach them for rapid orbital decay, and pick up a new set of customers. Figure 11 illustrates the concept. We do not consider this an outpost because the primary purpose of the r-OTV vehicle is to provide logistics and satellite servicing, not to host payloads; instead, hosting payloads is a potential minor line of business. Likewise, some of the outpost scenarios require the existence of such a vehicle; it would not make sense for one outpost to depend on the existence of another.

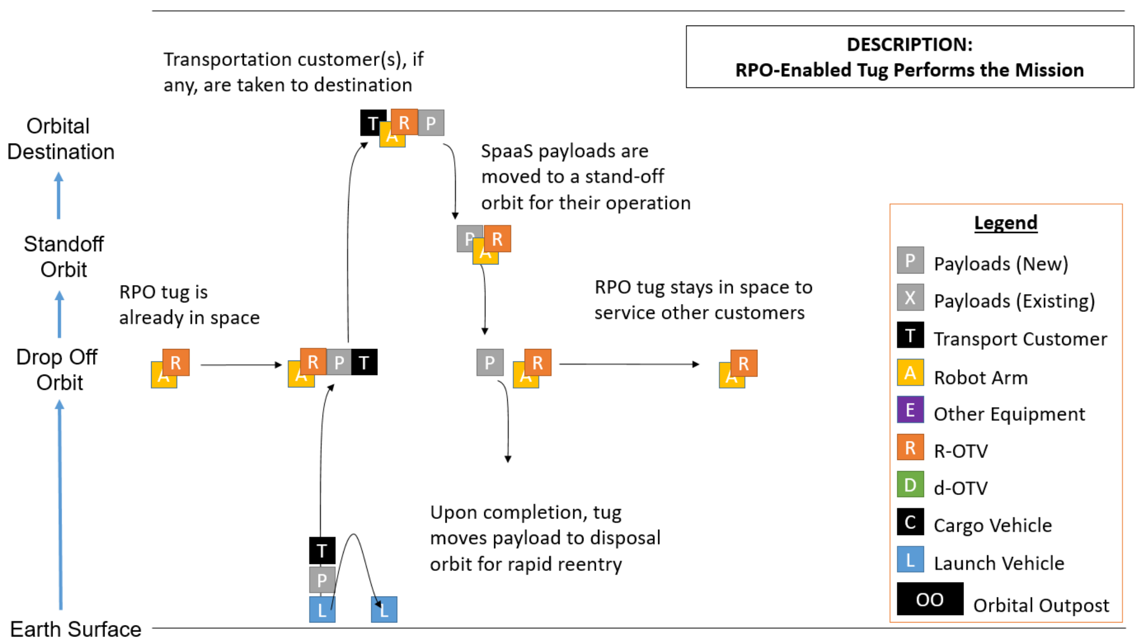

Figure 11. CONOPS for an r-OTV to Host the Payload

One advantage of this approach is that it likely reduces cost by removing the constraint that the r-OTV takes all test payloads to a specific orbit—where the outpost is. While an outpost could be positioned at an orbit that coincides with a highly demanded orbit for rideshare customers, in general, the r-OTV's customers may want to go to orbits other than where the outpost is located. It is a cumbersome and likely unnecessary constraint to make the r-OTV take all test payloads to the outpost's orbit, when the payloads could simply be tested onboard the r-OTV in the same orbit where the transportation customers were taken. Then the r-OTV need only ever travel to the LEO drop-off point and transportation destinations of other paying customers—never needing to add the outpost as a third destination. Costs associated with transits aboard an r-OTV are summarized in Table 18.

Table 18. Cost Associated with Launching and Hosting Payload on a R-OTV

Cost to LEO ($k/kg)		Cost to GEO ($k/kg)	
Low	High	Low	High
20	110	40	220

Note: See Appendix A for calculations

Unlike the scenario with the d-OTV, an r-OTV is likely to charge rent because there is a time-value to using it. Every day spent sitting still with a payload on board is a day spent not servicing other customers. As such, this scenario is likely only appropriate for short duration periods of hosting payloads.

3. Reusable Cargo Vehicle

A cargo vehicle is mainly appropriate for missions that need pressurized volume and the ability to return mass to the Earth. This may be the case for production of goods for sale in terrestrial markets and some types of microgravity R&D. In this scenario, the cargo vehicle launches with the payloads and any necessary equipment, loiters in space for a period of time, and returns the payloads safely to Earth. Figure 12 illustrates the scenario. The cargo vehicle may be a capsule that lands on the ground, splashes down in the water, or is caught in mid-air. The cargo vehicle may also be a spaceplane that returns payloads to a runway. The choice of vehicle will be driven by how robust the payloads are to forces associated with the different landing modalities. Microgravity R&D or production processes that do not require return mass are unlikely to use a reusable cargo vehicle.

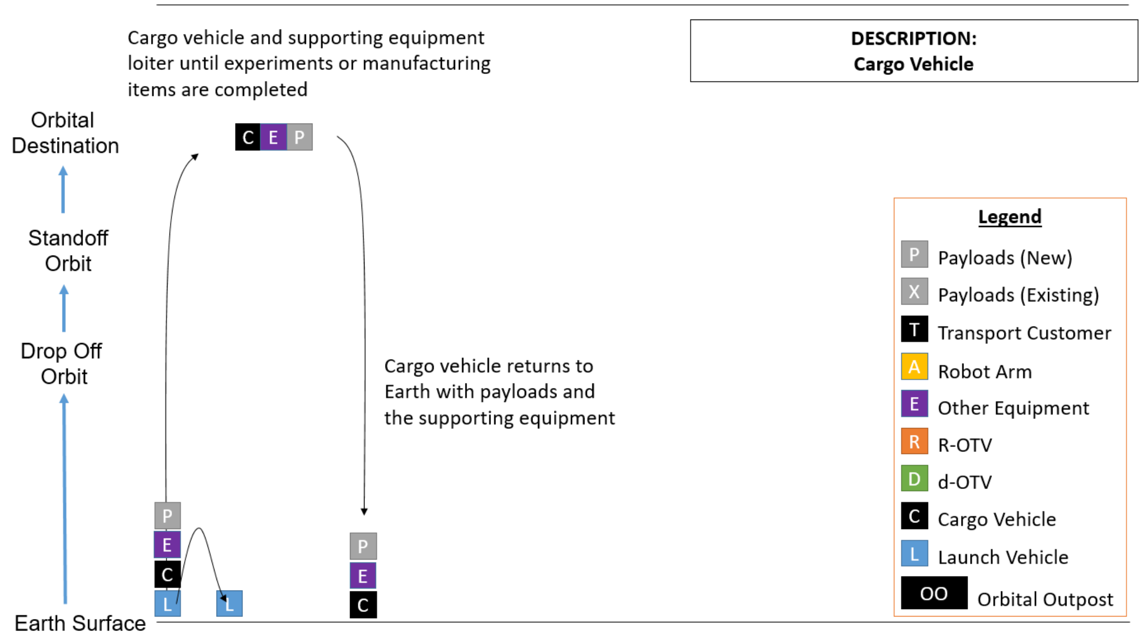

Figure 12. CONOPS for a Reusable Cargo Vehicle to Host Payloads

a. Microgravity R&D That Requires Down-Mass

We use a SpaceX Dragon as the main alternative to an outpost and calculate how many U of experiments it can host.[14] We place EXPRESS racks inside the cargo vehicle.[15] Each rack holds approximately 800 kg, including the experiments and all of the lab equipment required to support the experiments. Each EXPRESS rack holds about 9 MLEs, and there are 24U of experiments per MLE. Thus, it requires the launch of about 3.7 kg per U of experiment.[16] The Dragon has a total down-mass capability of about 3,000 kg, which implies that it can hold about 810 U of experiments.[17] The Dragon trunk can generate about 2kW of power on average and 4kW of peak power—nearly 2.5 Watts per U. This is reasonable as each U of payload on a CubeLab is allowed a maximum draw of 2 Watts (Kentucky Space 2011).

The costs associated with the hardware and launch for this scenario are shown in Table 19. There is no need for robotic arms or life extension in this scenario. Noting that a Dragon vehicle already has RPO capability, we subtract the cost of RPO from the total

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14 The Dream Chaser could equally be used; however, given the rough nature of the cost estimate, there is no need to provide multiple estimates. The Dragon costs are assumed to be reasonably representative.

15 See Appendix A for details regarding EXPRESS racks.

16 There are 216U of experiments (9 MLEs * 24U per MLE) and it requires 800kg to support them, including the mass of the payloads.

17 Dragon has the cabin volume to support many more U of experiments, but mass is the active constraint. Likewise, Dragon can launch more mass than it can return. Barring a method of jettisoning internal mass while in space, the down-mass capacity is the active constraint.

cost; there is no need for RPO in this scenario. For the purposes of analysis, we assume that fractional units of EXPRESS racks are possible; this allows us to make use of the entire down-mass capability of the Dragon.

Table 19. Hardware and Launch Costs for Microgravity R&D in a Pressurized Cargo Vehicle

Unit Name	Num Units	Unit Cost ($M)	Total Cost ($M)
Dragon	1	200	200
Life Extension	-	-	-
Robotic Arms	-	-	-
RPO Capability[a]	-1	20	-20
EXPRESS Racks[b]	3.75	5	18.75
Falcon 9 Launch	5	50	250
Total			**450**
Cost per Mission	**5 missions**		**90**

[a] Cargo Dragon already has RPO capability; however, it is not necessary for this mission. We subtract it out, as we do for use of a capsule as an outpost.

[b] An EXPRESS rack can hold 216U of experiments and the Dragon can hold 810U of experiments, thus it would take 810/216 = 3.75 EXPRESS racks to fill the Dragon.

To calculate the cost per U of experiment needed to cover hardware and launch costs (Table 20), we assume that the vehicle is completely filled with payloads. This represents our low-cost estimate. It may be difficult to coordinate 810U of experiments on the same platform due to scheduling and other operational constraints. We provide a high-cost estimate assuming that only one quarter of the Dragon's capacity (~200U) is taken by paying passengers.

Table 20. Representative Cost per U for a Cargo Vehicle to Perform Microgravity R&D

	Cost [$k][a]
Max Usage	110
Half Usage	220
Quarter Usage	440

Note: All costs rounded to two digits.

[a] Cost of the mission ($90 million) divided by the max (810 U) or appropriate usage rates.

b. Production

This situation is similar to the microgravity R&D with down-mass scenario. Unlike for microgravity R&D, where standardized interfaces are required to host various payloads, a cargo vehicle designed for manufacturing is likely optimized for a single user. We assume that the user will purchase an entire cargo vehicle and install their own custom equipment. After incorporating the mass of the production equipment, the rest of the vehicle's down-mass budget can hold preform materials that will be transformed into a saleable product while in space. As with microgravity R&D, any cargo vehicle could be used, so long as it provides the necessary power, mass, and volume for the production facility; for simplicity, we use a SpaceX Dragon as a representative cargo vehicle. Costs associated with the Dragon are discussed in Appendix A.

4. CubeSats

Not all experiments or payloads will require down-mass. We note that microgravity R&D experiments already occur on the Cygnus capsule, after it detaches from the ISS but before it reenters the atmosphere. However, the more general alternative to an orbital outpost is likely using a free-flying CubeSat. As described in Appendix A, CubeSats cost about $50,000 per U in hardware. In most cases, a 3U CubeSat will be able to host 1U of payload, with the other 2U taken by satellite subsystems.

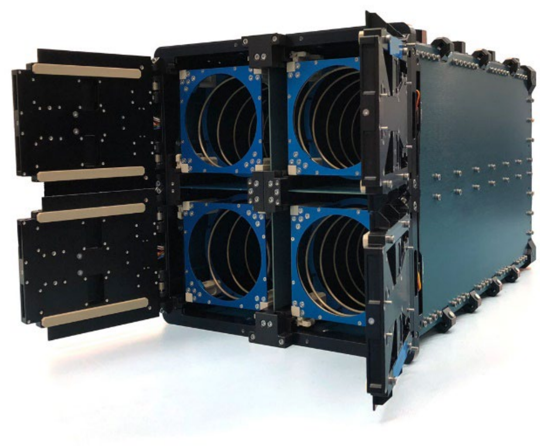

Figure 13. The QuadPack CubeSat Deployer from ISISPACE

The QuadPack CubeSat deployer from ISISPACE has a mass of 7.5 kg and can deploy 12U of CubeSats (ISISPACE n.d.). Factoring in the mass of the deployment mechanism, we assume that each U of payload deployed requires about 2 kg of mass to be launched.[18] In the appendix, we estimate that the cost of launching mass into LEO is $11,000–$25,000

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[18] The deployment mechanism is about 0.625 kg per U deployed (7.5 kg/12U). We round that up to 0.7 kg per U so that, when added to the 1.3 kg per U for the CubeSat hardware and payload, the total launch mass is 2 kg.

per kilogram. Thus, we estimate that launch costs are \$22,000– \$50,000 per U of satellite deployed.

3. Potential Activities

In this chapter, we review the various activities that might be conducted on an orbital outpost, estimate potential demand for those activities, and assess the utility of using an orbital outpost to conduct these activities compared to alternatives.

A. In-Space Testing and Demonstration

In-space testing is the ability to test space systems or subsystems in their intended operational environment. We identify three potential use cases for in-space testing: subsystem maturation, application demonstration, and adverse events testing. Subsystem maturation is the testing of space subsystems, such as batteries, solar panels, propulsion, and computing. Application demonstration is the use of space capabilities that are already relatively proven but have not yet been combined to demonstrate they are capable of delivering value or have not yet been demonstrated by U.S. entities. Adverse events testing exposes test articles to potential Red Threat environments. Threats may be cyber, electronic warfare, directed energy, kinetic, or nuclear.

1. Subsystem Maturation

The maturity of space technologies are roughly measured on a scale of 1–9, called technology readiness levels (TRLs). A technology that is at TRL 1 is at the stage of basic scientific research, in other words, an idea that seems plausible and does not violate any of the laws of physics. At TRL 7 a technology begins to be considered mature: a flight design of the integrated system has been developed and successfully tested in an operationally relevant environment. At the highest level of maturity, a system at TRL 9 has been incorporated into an operational mission and proven to be reliable. Government programs and private investors generally do not commit to incorporating technologies below TRL 7 into the critical path of their operations. In other words, a space technology must first be tested in a space-like environment before it can begin to transition into operations.

Ground testing of prototypes can raise the maturity of a space technology up to TRL 7, as is generally the case with propulsion systems. However, for some classes of space hardware, the operation of a prototype or integrated system in the space environment is the most convincing method to achieve this maturity level. By conducting in-space tests, innovative technologies can be easily transitioned into government programs for broad adoption. The technical risks of the technology will be effectively retired, opening the door to broad investment opportunities from the private sector.

To characterize the features needed for such a test, we analyzed a list of approximately 150 potential candidates for in-space developmental testing gathered by the Department of Defense's (DoD) Space and Missile Systems Center (SMC). Not all of the payloads on the list require in-space testing nor do they require the use of an orbital outpost. We categorized the payloads and assessed their need for a persistent platform in space. The list includes approximately 17 categories of test candidates that might be appropriate for use on an orbital outpost. The results are summarized in Table 21, with more details on the analysis and the categories in Appendix B: Analysis of SMC's Test Candidate List.

None of the space test articles require a pressurized volume; such articles may exist, but they are likely testing capabilities related to human spaceflight participants—who must necessarily inhabit a pressurized volume—and thus the technologies would most likely be tested on a crewed station with the crew in the testing loop. The payloads we identified do not require return-mass to Earth. Most payloads did not provide pointing requirements; however, they generally do not appear to require tight pointing requirements. Some payloads in the database do have pointing requirements, but they appear to be operational missions to gather remote sensing or space science data—not to test hardware. Power levels demanded by the test articles are reasonably within the range of what can be provided by various outpost alternatives. The largest test payloads found in the database, such as for deployable systems and cryogenic management, have already been launched and were hosted on the ISS—one of the alternatives to an outpost—as external payloads. Such payloads are also within the mass range of d-OTVs.

Table 21. Summary of Representative iSDT Payloads

Capability	Mass [kg]	Power [W]	Duration [months]	Orbit
Battery	1	10	>12	LEO
Beacon	1	10	6	LEO
Clocks	20	50	6	LEO
Comms (GEO)	80	1,000	12	GEO
Comms (LEO)	10	50	3	LEO
Computing	10	50	6	LEO
Cryogen Management	150	500	6	LEO
Deployable Systems	150	100	3	LEO
Directed Energy Resilience [a]	-	-	-	-
Electric Propulsion	10	500	3	LEO
Interface for Sat Servicing	6	500	3	LEO
Laser Systems [a]	-	-	-	-
Power Generation [a]	-	-	-	-
Sensor – Infrared Radiation [a]	-	-	-	-

Capability	Mass [kg]	Power [W]	Duration [months]	Orbit
Sensor – Meteorology [a]	-	-	-	-
Sensor – Remote Sensing	45	100	12	LEO
Sensor – Space Weather	15	50	>12	LEO
Space-Based SSA [a]	-	-	-	-

a. We were unable to associate technical specifications with some of the capabilities to be tested.

Most of the technologies to be tested do not appear to require a persistent platform compared to alternatives. Further, most technologies do not appear to require access to GEO orbits. As such, the decision to use an orbital outpost in this case will be driven by cost. We investigate the costs associated with short-duration experiments, lasting less than 1 year, and long-durations experiments that last more than 1 year. For both types of experiments, we use a building block outpost as it can satisfy the relatively low-power needs of the potential payloads and it has a lower monthly rent than a CondoSat. Access to LEO is cheaper than traveling to GEO; thus, the outposts are assumed to be in LEO.

Estimated costs associated with various SpaaS scenarios for short-duration experiments in LEO are shown in Table 22. The table is organized by the type of in-space transportation vehicle that might be used to ferry the payload to an outpost. There are four options—low-cost d-OTVS, high-cost d-OTVS, low-cost r-OTVs, and high-cost r-OTVs. The first transportation option shows the costs associated with using a low-cost d-OTV. For this vehicle, the cost of delivery to a desired orbit is $11k/kg. As described previously, a d-OTV effectively does not charge rent; all of its hardware and launch costs are covered by the cost of the transportation services it provides. However, if the payload is transferred to an outpost, the payload owner will have to pay rent. For d-OTVs, the destination outpost must have RPO capability to receive the payload. The other transportation options follow the same logic. We note that if an r-OTV can be used to deliver the payload to orbit, the recipient outpost does not need to have RPO or robotic manipulation capabilities.

Table 22 illustrates that, even for the shortest possible stay on an outpost, hosting the payload on a d-OTV always outperforms an RPO-capable outpost. This relationship holds true for any mass of payload and the outpost becomes less attractive the longer the duration required, up to the operational lifetime of the d-OTV. Likewise, an r-OTV serving the stripped down outpost—no RPO capability and no arms—is less economic than simply leaving the payload on the r-OTV. If the cost of using an r-OTV drops below the cost of using a d-OTV, then the r-OTV might become the most cost competitive option. In general, there is no need for a short-duration test payload to step off of its d-OTV or r-OTV, so there is no reason for it to incur the added cost of rent on an outpost.

A potential advantage of hosting short-duration test payloads on an r-OTV, unlike a stand-alone outpost, is that the r-OTV may not need to host a large number of test articles to reach economic feasibility. An outpost that must operate many test payloads simultaneously has a difficult scheduling problem to overcome. For example, tests involving thrusters and sensitive optics would be challenging to test simultaneously as exhaust from the thruster may contaminate the optics. These types of scheduling issues make it challenging to reach the high number of customers required for a stand-alone outpost to be viable. On the r-OTV, a smaller number of payloads can be tested per mission, potentially in sequence, reducing scheduling conflicts. Testing of propulsion systems may also be used, perhaps, for transportation to its next customer; this would allow the r-OTV to simultaneously test a payload and reduce the propellant it expends to reach its new customers.

Table 22. Cost Comparison for Subsystem Maturation: Short-Duration Experiments in LEO

Scenario [Cost Level]	Transport [$k/kg]	Rent [$k/month] [b]	Total [$k][a]
Transportation Option #1			
d-OTV [Low Cost][c]	11	0	110
Building Block with RPO [Low Rent]	11	65	175
Building Block with RPO [High Rent]	11	360	470
Transportation Option #2			
d-OTV [High Cost] [d]	25	0	250
Building Block with RPO [Low Rent]	25	65	315
Building Block with RPO [High Rent]	25	360	610
Transportation Option #3			
r-OTV [Low Cost] [e]	25	0	250
Building Block – Stripped Down [Low Rent]	25	15	265
Building Block – Stripped Down [High Rent]	25	30	280
Transportation Option #4			
r-OTV [High Cost] [f]	115	0	1,150
Building Block – Stripped Down [Low Rent]	115	15	1,165
Building Block – Stripped Down [High Rent]	115	30	1,180

a. All values calculated for a payload mass of 10kg and a length of stay of 1 month.

b. Note that the rent numbers for both vehicles do not include operational and amortized development costs, which we deliberately omit. Such costs are likely less for the d-OTV than the outpost; thus, if the outpost is not cost competitive with these costs omitted, then it will not be competitive with such costs included.

c. $5k/kg for the launch from Earth and $6k/kg for the low-cost d-OTV to take the payload to the final orbit.

d. $5k/kg for the launch from Earth and $20k/kg for the high-cost d-OTV to take the payload to the final orbit.

e. $5k/kg for the launch from Earth and $20k/kg for the low-cost r-OTV to take the payload to the final orbit.

f. $5k/kg for the launch from Earth and $110k/kg for the high-cost r-OTV to take the payload to the final orbit.

Estimated costs associated with various SpaaS scenarios for long-duration experiments in LEO are shown in Table 23. Specifically, the table assumes a test duration of 18 months and a test article mass of 60 kg.[19] The main difference between long and short- duration tests is that for test lasting greater than a year, a normal d-OTV may not have the operational lifetime to host the payload. For the first transportation option in Table 23, we must use the cost associated with a d-OTV that has had its operational lifetime extended to host the payload.[20] However, an extended life d-OTV is not required to simply transport the payload to an outpost; thus, the rows associated with hosting the payload on an outpost use the costs of d-OTVs that lack life extension capabilities—the same costs used in the previous table. A similar logic applies to the second transportation option, where high-cost d-OTVs are used. Just like for short-duration experiments, hosting the payload on a d-OTV significantly outcompetes the use of a building block outpost for all payload masses and test durations.

Table 23. Cost Comparison for Subsystem Maturation: Long-Duration Experiments in LEO

Scenario [Cost Level]	Transport [$k/kg]	Rent [$k/month] [b]	Total [$k][a]
Transportation Option #1			
d-OTV Extended Life [Low Cost][c]	25	0	900
Building Block with RPO [Low Rent] [d]	11	65	1,830
Building Block with RPO [High Rent] [d]	11	360	7,140
Transportation Option #2			
d-OTV Extended Life [High Cost] [e]	35	0	2,100
Building Block with RPO [Low Rent] [f]	25	65	2,670
Building Block with RPO [High Rent] [f]	25	360	7,980
Transportation Option #3			
r-OTV [Low Cost] [g]	25	-	-
Building Block – Stripped Down [Low Rent]	25	15	1,770
Building Block – Stripped Down [High Rent]	25	30	2,040
Transportation Option #4			
r-OTV [High Cost] [h]	115	-	-
Building Block – Stripped Down [Low Rent]	115	15	7,170
Building Block – Stripped Down [High Rent]	115	30	7,440

[19] These values were chosen to illustrate the regime in which an r-OTV may become cost-competitive.

[20] See Appendix A for details on the cost of an extended life d-OTV.

[a] All values calculated for a payload mass of 60kg and a length of stay of 18 months.

[b] The rent numbers for both vehicles do not include operational and amortized development costs, which we deliberately omit. Such costs are likely less for the d-OTV than the outpost; thus, if the outpost is not cost competitive with these costs omitted, then it will not be competitive with such costs included.

[c] $5k/kg for the launch from Earth and $10k/kg for the low-cost d-OTV with extended life.

[d] Uses low-cost d-OTV without extended life.

[e] $5k/kg for the launch from Earth and $30k/kg for the high-cost d-OTV with extended life.

[f] Uses high-cost d-OTV without extended life.

[g] $5k/kg for the launch from Earth and $20k/kg for the low-cost r-OTV to take the payload to the final orbit.

[h] $5k/kg for the launch from Earth and $110k/kg for the high-cost r-OTV to take the payload to the final orbit.

The transportation options in Table 23 that use an r-OTV are qualitatively different from the short-term experiments discussed previously. As the experiment duration is 1 year or greater, the assumption of zero rent on an r-OTV is no longer reasonable. There is a significant opportunity cost if the r-OTV must remain stationary for the duration of the experiment, rather than generating revenue by serving other customers. In this case, an r-OTV operator will have a strong incentive to transfer the payload to the stripped-down building block outpost.

For small masses, the r-OTV with the stripped down building block is not economic compared to the use of a low-cost d-OTV; however, there is a narrow window of opportunity for a stripped down building block to beat the d-OTV as the most economic option. As the mass of the test payload increases, the stripped down building block becomes more economical. Specifically, for a test length of 18 months, the high-cost building block with a low-cost r-OTV breaks even with the high-cost d-OTV at a payload mass of 60 kg. Costs break even for test lengths of 24 and 36 months at payload masses of 80 kg and 110 kg, respectively. The niche for an outpost is thus high-mass, long-duration tests and requires the existence of a low-cost r-OTV. Few test payloads appear to meet these requirements.

In a competitive marketplace that is unsubsidized, payload owners are incentivized to make their tests as short as possible, likely bringing nearly all payloads to have short-duration tests, where a d-OTV is the clear winner. One caveat to this assertion is that after proving successful, a test article may be able to generate value by gathering data or possibly even entering into an operational capacity. This is a somewhat common practice now, where the entire costs associated with development and launch of the spacecraft hosting the test article are sunk at the time of launch; thus, the marginal cost of continuing to operate is relatively small. In contrast, on an outpost, every extra month of operations also incurs a rental fee that incorporates further amortization of the hardware and launch costs, as well as the other costs we have omitted from our rent calculations. These costs quickly become substantial, and the owner of the test article may not have budgeted for a longer period of operations. Further, long duration tests on an outpost become economic only with a low-cost r-OTV, which seems less likely than a low-cost long-duration d-OTV. As an outpost does not clearly serve a niche for subsystem maturation, we find that the market size is likely too small to estimate.

In the near term, there may be developmental testing customers for an orbital outpost, but that may be because the SpaaS concept does not yet have high visibility in the community. We found interviewees were somewhat surprised to hear that Xplore, Momentus, and Loft Orbital may be capable of providing such services. Once the market matures and payload owners gain a better understanding of future SpaaS capabilities, we think they will prefer disposable platforms rather than pay for a portion of the costs associated with robotic arms and RPO capabilities, which do not clearly benefit the payload owner.

2. Application Demonstration

Application demonstration is the use of space capabilities that are already relatively proven but have not yet been combined to demonstrate they are capable of delivering value or have not yet been demonstrated by U.S. entities. Examples may include the use of robotic arms for assembling structures in space from pre-fabricated components (e.g., OSAM-1) or the combination of robotic arms and additive manufacturing for manufacturing and assembling novel structures (e.g., OSAM-2). Users could send trusses, joints, and fasteners for the arm to assemble. Users might test new control algorithms for the arm. The outpost might become an additive manufacturing testbed that could be used by customers to iterate on designs for space-optimized structures.

Another possibility is to use a simple stand-alone outpost to facilitate testing of r-OTVs, docking interfaces, RPO, and other aspects of on-orbit servicing. The outpost would provide a target on which various r-OTV prototypes might practice with reduced fear of damage.[21] However, the aforementioned tests of r-OTVs could also take place by rendezvousing with defunct satellites or disposable tugs; this option is likely more cost effective as the rendezvous targets would have already been paid for by the original customers and are now space debris. Therefore, we focus our analysis on the previously mentioned testing of robotic arms and in-space assembly and manufacturing.

As a baseline, we construct a scenario where a robotic arm is placed on a d-OTV and various researchers rent time on the arm. For this situation, we calculate an effective monthly rent that amortizes the unit and launch costs of the arm over the 12 months that the d-OTV is assumed to be operational. The effective monthly rent is calculated using the same assumptions as the outposts, that there are 3–6 simultaneous customers and each

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[21] As the r-OTVs would be traveling to the outpost already as a part of their own testing, they could take iSDT payloads with them as rideshares and transfer them to the outpost. In this case, iSDT payloads similar to those discussed earlier might provide a small amount of revenue to offset the costs of testing r-OTVs and outposts; however, we do not analyze this case as it is likely a small amount of revenue.

might only need access to the platform for as little as 1 month. Each user is assumed to send a small amount of mass (10 kg) along with the arm, such as new end-effectors, tools, and other objects to manipulate or assemble. This effectively establishes the cost to beat.

Table 24 illustrates the relative costs associated with performing the demonstrations for various SpaaS scenarios, each for a test duration of 1 month. For the transportation options that use a d-OTV to transport the test articles, building block outposts generally outcompete scenarios where the arm and test articles are resident on the d-OTV by a wide margin. A high-cost r-OTV is unlikely to ever be used for this activity as it is almost always more expensive than scenarios that use an outpost. We find that low-rent building blocks are generally cheaper or of comparable cost to low-cost r-OTVs. Low-rent building blocks become increasingly economic as payload mass increases. For small payload masses, such as shown in the table, high-rent building blocks are more expensive than low-cost r-OTVs; however, this effect diminishes as payload mass increases. Further, we find it unlikely that an r-OTV would be an appropriate platform for these types of experiments; the r-OTV operator is unlikely to allow other users to take control of their robot arms or install experimental end-effectors. As such, a building block outpost is likely the most competitive option for hosting these types of experimental demonstrations.

In our previous calculations of the rent for a building block outpost, we had assumed 3–6 simultaneous customers; however, only one customer can use an arm at a time. This presents potential scheduling difficulties, but due to the relatively low number of total customers, this may still be feasible. The scheduling concerns are compounded as the number of simultaneous customers increases; therefore, we do not consider the use of other, more populated outpost scenarios.

Table 24. Cost Comparison for Application Demonstration

Scenario [Cost Level]	Transport [$k/kg]	Rent [$k/month]	Total [$k][a]
Transport Option #1: Low Cost d-OTV			
d-OTV with Arm [Low Rent][b]	11	210	330
Building Block with RPO [Low Rent]	11	65	175
d-OTV with Arm [High Rent][b]	11	1,700	1,800
Building Block with RPO [High Rent]	11	360	470
Transport Option #2: High Cost d-OTV			
d-OTV with Arm [Low Rent][c]	25	210	460
Building Block with RPO [Low Rent]	25	65	315

Scenario [Cost Level]	Transport [$k/kg]	Rent [$k/month]	Total [$k][a]
d-OTV with Arm [High Rent][b]	25	1,700	1,950
Building Block with RPO [High Rent]	25	360	610
Transport Option #3: Low Cost r-OTV			
r-OTV	25	0	250
Transport Option #4: High Cost r-OTV			
r-OTV	115	0	1,150

a. All values calculated for a payload mass of 10kg per user and a length of use of 1 month.

b. Effective low-cost rent amortizes one low-cost arm ($15 million) over 6 users per month for 12 months.

c. Effective high-cost rent amortizes one high-cost arm ($60 million) over 3 users per month for 12 months.

The use of a robotic arm for in-space testing is somewhat proven already with the Special Purpose Dexterous Manipulator (SPDM) onboard the ISS. It is a small robotic arm used for performing space station repairs and occasionally testing new technologies. However, interviewees indicated that SPDM is not a good platform for robotic tests because potential users must use MDA's control stack, without being given insight into the details of the control stack or opportunities to customize it. For a robotic arm to be an attractive test instrument, the owner of the arm would need to use a more transparent and customizable approach to the control of the arm.

3. Adverse Events Testing

Adverse events testing exposes test articles to potential Red Threats. Threats may be cyber, electronic warfare, directed energy, kinetic, or nuclear. Interviewees indicated that most space system testing is performed by the contractor developing the system and does not adequately test the ability of the system to operate in a contested domain. Such tests may allow better characterization of an adverse event, thus improving attribution, and may lead to more resilient designs for space systems or new tactics, techniques, and procedures (TTPs) to mitigate threats. Defense users could own and operate an outpost for red teaming and resilience testing. In this case, accidental or intentional damage to solar panels or other sensors can be readily fixed; new components can be flown to the outpost to replace the damaged components. This use case has a high degree of overlap with the two previously described applications, but it would require unique capabilities that are relevant only to defense users. Due to the nature of threat testing space systems, we are unable to analyze this application area in depth. However, we provide the following considerations.

Of the five use cases mentioned earlier, we assume that directed energy and kinetic threats are likely the most appropriate for use with in-space testing. Resilience against directed energy threats may benefit from in-space testing because of the complexities of thermal management issues due to impinging radiation and the effects of the ionosphere on the beam. Likewise, the ability to track and respond to potential kinetic threats may benefit from in-space tests of tracking sensors and methods of intercept or avoidance. Cyber, electronic warfare, and nuclear threats seem to be more appropriate for ground-based and virtual testing.

Due to the sensitive nature of these tests, we find it unlikely that defense users would be willing to share the platform with commercial or non-defense government users. Likewise, due to the adverse nature of these tests, only payloads that are being threat-tested are likely to use the platform. For instance, most payloads would not want to be on a platform that is being subjected to a directed energy attack. Thus, a defense user that chooses to use a persistent platform for these tests would have to purchase and operate an entire outpost.

For directed energy testing, we envision that potential payloads might include solar panels, avionics modules, communications models, and sensors—anything that might be damaged by an energy beam. After a test, engineers can assess damages and send up design iterations or replace damaged subsystems. Alternatively, if there is a campaign to test a set of flight articles, all of the test articles could be flown up at once and installed sequentially for testing. We are unable to assess the degree to which ground-testing is the most appropriate form of testing for this use case.

If a defense user deems in-space testing a requirement, however, then we can analyze alternatives for in-space testing. Ideally, the satellite systems tested in a directed energy simulation would be as close as possible to the operational satellite. That would mean flying substantially similar avionics, solar panels, communications, and other sensors that are all hooked together. Further, the defense user would likely want the ability to control the spacecraft to test TTPs to mitigate the effects of the threat. These features seem unlikely to be possible with a d-OTV or r-OTV. Thus, the main alternative we investigate is integration of the test articles into traditional satellites.

Table 25 shows the costs of executing a campaign that tests 10 solar panels, for example. The bus for a low- or high-cost building block outpost is a Blue Canyon X-Sat, which has 800W of power. For the building block scenarios, we assume that the first solar panels sent up will be tested, followed by nine replacement missions. Each of the replacement missions uses a launch price associated with small launch vehicles like Astra. Additionally, we launch the required modules for other subsystems (e.g., communications, avionics) on a small launch vehicle. We assume these modules are not damaged during tests and could be reused. Using consistent assumptions, we also estimate the cost of launching 10 identical ESPA-class satellites for use on the tests.[22]

For a test campaign of 10 articles, it appears that even the high-cost building block outpost is the more economical approach. The low-cost building block becomes the more economical approach on the fourth test (not shown). These relationships are approximately preserved under similar scenarios where, instead of replacing solar panels, other modules with masses of approximately 25 kg are replaced. In addition to potential cost savings, it is likely that the test campaign could be executed more rapidly with an outpost than with separate ESPA-class satellites that must wait for rideshares to get to space.

After the test campaign, the defense user may have options to recoup some of their investment if the platform is still in good shape. One option would be to remove their modules and sell the empty outpost to a different customer for their use. Alternatively, the user could commit to using the outpost as a platform on which to host operational capabilities. After sufficient testing, the entire outpost platform might become sufficiently hardened to the point that its owner might transition to using the platform for operational missions. Further, the design of the test outpost could be frozen and operational satellites manufactured to replicate the design. Components, however, are unlikely to be swapped in and out during the operational phase of the mission; the value of the outpost scenario here is that it allows for more rapid testing of a design against adverse effects capabilities. This CONOPS does not simply reap the benefits of satellite modularity, but also the ability to hot-swap the modular components on orbit. This scenario seems promising; however, we are unable to evaluate whether this approach would be cost effective compared to a campaign of ground tests.

Table 25. Cost Comparison for Test Campaign of Directed Energy Threats on Solar Panels

Scenarios	Units	Unit Cost [$k]	Mass [kg]	Transport Total [$k]	Hardware Total [$k]	Total [$k]
Purchase Building Block [Low][a]						46,000
Replace Solar Panels [d]	9	800[c]	6	1,350	7,200	8,550
Other Modules [d]	1	10,000	100	2,500	10,000	12,500
Total						**67,050**
Purchase Building Block [High][b]						**130,000**
Replace Solar Panels[e]	9	800[c]	6	1,350	7,200	8,550
Other Modules[e]	1	10,000	100	2,500	10,000	12,500

[22] An Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adapter (ESPA) is a ring-shaped piece of hardware that allows secondary payloads to be launched as rideshares on orbital launch vehicles. An ESPA-class satellite is one that is able to attach to an ESPA ring as a secondary payload.

Scenarios	Units	Unit Cost [$k]	Mass [kg]	Transport Total [$k]	Hardware Total [$k]	Total [$k]
Total						**151,050**
Use Multiple ESPA-class Tests						
Blue Canyon X-Sat Bus [f]	10	5,000	150	16,500	50,000	66,500
Other Modules[f]	10	10,000	100	11,000	100,000	111,000
Total						**177,500**

a. Total cost taken from Table 3 in Chapter 2.

b. Total cost taken from Table 3 in Chapter 2.

c. A subject matter expert gave us a heuristic for costing solar panels: $1 million per kilowatt. Thus, an 800-Watt panel would cost approximately $0.8 million.

d. Launch costs are $25k/kg for a rapid launch; no d-OTV is used.

e. Launch costs are $25k/kg for a rapid launch; no d-OTV is used.

f. Launch costs are $5k/kg for launch from Earth and then $6k/kg for use of a low-cost d-OTV.

Interviewees agreed that adverse events testing is an important function; however, it is our understanding that there are no requirements[23] for such testing to occur in space. Without a requirement to perform adverse events testing, programs of record may not budget the time and resources to perform such a test. Thus, these tests are likely to occur outside of program of record, as part of general R&D at relatively early levels of TRL. We described our illustration of the directed energy test campaign on solar panels with an interviewee that performs satellite R&D; they commented that while our example was plausible, a campaign of smaller satellites—such as CubeSats with small solar panels—would likely work just as well and be cheaper.

4. Potential Market for In-Space Testing

Revenues for subsystem testing are unlikely to be captured by an outpost in a competitive market without subsidies for launch or the operation of payloads. However, the demonstration of applications, such as testing the control and use of robotic arms, could be viable. Interviewees indicated that at a price of about $0.5 million per experiment, substantial revenues could be unlocked. Internal R&D projects within service labs can typically be about $1.5 million over a few years. At a cost of $0.5 million, that would allow for about $1 million to be spent on the design of the experiment and manufacturing of the test hardware (e.g. end effectors, tools, or parts to assemble) with budget left over to test the system in space. Likewise, the maximum Small Business Innovation Research (SBIR) Phase II award from the U.S. Air Force (USAF) is approximately $1.6 million using the

23 By requirements, we mean those that have been validated through the Joint Capabilities Integration and Development System (JCIDS).

direct-to-phase-II mechanism (USAF 2019), which would be sufficient for private companies to perform similar experiments.

For the low-cost building block outpost, our hardware and launch cost estimates come in well below the $0.5 million threshold. It is reasonable that the final price to end-users—incorporating costs associated with development, program management, and operations—would remain under $0.5 million. The low-cost price point assumes 6 customers per month, every month, for 10 years. That is 72 customers annually. At a price of $1.5 million per customer, that would lead to an annual budget for robotics research of about $110 million. This mission cadence and budget seems reasonable with coordination between DoD's service labs, DoD's SBIR program, and NASA's On-orbit Servicing, Assembly, and Manufacturing (OSAM) Office.

For the high-cost building block outpost, our hardware and launch cost estimates are just below the $0.5 million threshold. It is unlikely that the final price to end-users would be below the threshold without substantial subsidization of the platform. However, we note that the cost-driver of the high-cost outpost is the number of customers, which is assumed to be 3 per month for 10 years—36 users per year. This cost driver is within the government's control and depends on the annual amount of research funding allocated to space robotics. For example, assume that the final price to users is approximately $1 million per month to use the outpost and that experiments cost about $1 million to develop, as previously assumed, for a total test budget of $2 million. This leads to an annual government research budget of $72 million to reach 36 customers per year. The government may find it prudent to pay 50 percent more (i.e., $110 million) in exchange for 100 percent more annual experiments (72). However, the reduced budget option may still be feasible if service labs can secure research budgets of $2 million and DoD's direct to Phase II SBIR awardees co-invest some of their resources to hit the $2 million mark.

We find that adverse events testing using an outpost might deliver value compared to alternatives, but that it is more likely to be for testing of operational systems than for lower-level R&D. We are unable to estimate the potential revenue for these activities. We simply note that the hardware costs associated with running a full test campaign on the satellite are well below the costs of an operational satellite for the DoD. Factoring in the costs that we have not calculated may still yield a system within typical program budgets. The main issue is whether DoD users would find value in such an in-space test campaign. The trend toward disaggregation and proliferation of space systems may remove the need for a single hardened space asset. To stimulate demand for an outpost, the DoD could require or otherwise incentivize threat testing for operational systems under development. Likewise, if programs of record committed to using a modified outpost as the bus for their operational systems, the value of in-space testing on an outpost would be magnified.

B. Technology Refresh

Satellites can suffer anomalies and fail at unpredictable times. The failure of a single sensor may compromise the entire mission of a satellite. A modular satellite that is designed for hardware to be replaced while on orbit offers the potential to mitigate the risk of such failures. By integrating their sensors into a small outpost bus, the satellite owner may be able to replace their faulty sensor on orbit, rather than building and launching a newly integrated satellite. Likewise, after a few years of nominal operations, the satellite owner may wish to upgrade the technology on board their spacecraft (e.g., sensors or compute modules) without building a new satellite.

This capability has already been somewhat proven by the MultiMission Modular Spacecraft (MMS) program, which developed a modular satellite bus having its major subsystems standardized and modularized. For example, the Solar Maximum Mission used the MMS platform and was launched in 1980; however, the satellite's attitude control module failed only months later, ending the mission. In 1984, astronauts aboard Space Shuttle Columbia captured the malfunctioning satellite and hot-swapped a new attitude control module into the satellite. With the satellite restored, the Solar Maximum Mission proceeded until the satellite reentered the atmosphere in 1989.

In the previous example, the main potential benefit may be simply having the ability to mitigate an instrument failure. Large communications satellites may be another fruitful application for an outpost, due to a likely stronger incentive to refresh technologies frequently. The ability to periodically upgrade antennas or compute modules may allow a satellite to take advantage of the latest advances, rather than being stuck with outdated capabilities for the majority of the satellite's lifetime.

Potential use cases for this capability span all activities for which satellites are used, such as Earth observation, space science, and communications. For this analysis, we mainly focus on Earth observations, which are activities that consist of scientific measurements of geophysical and Earth system science processes to collect atmospheric, oceanic, or terrestrial data about the planet (Group on Earth Observations 2020). These observations include space-based or remotely sensed data, as well as ground-based data. Earth observations can use radar, laser imaging, optical and multispectral sensors, among others, and can be performed from a number of platforms, such as satellites, aircraft, and unmanned aerial vehicles (Tomas and Li 2017).

To analyze the utility of technology refresh, we investigate two potential scenarios. First, using a small outpost as a replacement for a small satellite. Second, using a large outpost as a replacement for a large satellite. We analyze the satellites in GEO, because if they are not cost effective in GEO, then they will not be cost effective in LEO. Alternatively, if they are cost effective in GEO, then they will be cost effective in higher orbits than GEO.

1. For Small Satellites

To analyze this use case, we build on the work of Mukherjee et al. (2020) and their concept of an orbital science station, which is robotically assembled and serviced, for replacing satellites in the A-train. The A-train is a constellation of satellites that performs Earth observation measurements in a Sun synchronous polar orbit in LEO. We draw from the instruments on the A-train (Table 26) to understand their potential costs, masses, and power needs. We assume that the characteristics of these instruments are general enough that we will use the same instrument specifications for all potential orbits, not just in LEO.

The payloads used for a science station may require up to 550W of power, though about half will require less than 200W. In addition to power, Earth observation instruments will need relatively high data rates, such as a 25 megabit per second (mbps) orbital average, possibly as high as 40 mbps in one case. In addition to being able to communicate the data collected, a payload may require onboard data processing capabilities. Depending on the payload, there may be additional requirements regarding the aperture size, field of regard, and accuracy. The mass of these instruments may be up to 490 kg or as little as 50kg.

Table 26. Instruments in the A-train

Satellite	Instrument	Instrument Mass [kg]	Instrument Power [W]	Design Life [years]
OCO-2		135	125	2
GCOM-W1		405		5
Aqua	AIRS (NASA)	177	220	6
Aqua	AMSR-E (JAXA)	314	350	6
Aqua	AMSU (NASA)	91	101	6
Aqua	HSB (INPE)	51	80	6
Aqua	CERES (NASA)	100	103	6
Aqua	MODIS (NASA)	229	162	6
Aura	MLS	490	550	6
Aura	HIRDLS	220	220	6
Aura	OMI	65	66	6
Aura	TES	385	334	6

For an economic comparison, we use two price points from instruments from the Aqua satellite to estimate the cost of a representative payload. On the lower end, we use the Humidity Sounder for Brazil (HSB) instrument, which according to Federal contracting data was contracted out to Matra Marconi Space to build for $10M in 1997, equivalent to $16.65M in 2021 dollars. Based on this example, we assign our low-cost payload a mass of 50kg and a cost of $20 million. For the higher end of instrument payloads, we use the Atmospheric Infrared Sounder (AIRS) instrument, which was contracted out to Lockheed

Martin Infrared & Imaging Systems (LMIRIS) for $145M in 1991, which is equivalent to $248M in 2021 dollars. Thus, we assign our high-cost instrument a mass of 175kg and a cost of $250 million.

Some satellites in the A-train can be relatively small, containing only a single instrument. For this case, we assume that the satellite has one low-cost instrument, based on the HSB previously discussed. The instrument is integrated into a small satellite bus. If the instrument fails, a new spacecraft must be built and flown to replace the defunct instrument. This establishes the cost an outpost must beat to be competitive.

The most appropriate outpost would be a building block outpost. We assume that the user buys the entire system, instead of trying to share with other customers. The system launches with a low-cost instrument already integrated. The user will only send a new instrument up in the event of a failure or some other need for a technology refresh. Table 27 shows the costs associated with the cost to beat, the outpost scenarios we consider, and the costs associated with refreshing an outpost. A building block outpost would be refreshed by a d-OTV, while a stripped down building block can only be refreshed by an r-OTV.

In general, users of an outpost for technology refresh capabilities are likely driven by reducing cost, rather than accelerating schedule. Indeed, for the case of an instrument failure, it will take time to rebuild the instrument. However, a payload owner that wishes to recover quickly from a failure may build spares of the instruments aboard the spacecraft that can be rapidly deployed if needed.

Table 27. Hardware and Launch Costs for Nominal and Single-Refresh Scenarios of a Small Satellite in GEO

Scenarios	Units	Unit Cost [$k]	Mass [kg]	Transport Total [$k]	Hardware Total [$k]	Total [$k]
Small Satellite – Cost to Beat[a]						
Small Bus	1	5,000	150	4,500	5,000	9,500
Low Cost Instrument	1	20,000	50	1,500	20,000	21,500
Total						**31,000**
Building Block[a]						
Outpost Bus [Low Cost]	1	45,000	225	6,750	45,000	51,750
Low Cost Instrument	1	20,000	50	1,500	20,000	21,500
Total						**73,000**
Building Block – Stripped Down[a]						
Outpost Bus [Low Cost]	1	10,000	150	4,500	10,000	14,500
Low Cost Instrument	1	20,000	50	1,500	20,000	21,500
Total						**36,000**

Scenarios	Units	Unit Cost [$k]	Mass [kg]	Transport Total [$k]	Hardware Total [$k]	Total [$k]
Refresh Instrument with d-OTV[a]						
Low Cost Instrument	1	20,000	50	1,500	20,000	21,500
Total						**22,000**
Refresh Instrument with r-OTV[b]						
Low Cost Instrument	1	20,000	50	2,750	20,000	22,750
Total						**23,000**

Note: All total costs (in bold) are rounded to two digits

a. Transportation costs are $15k/kg to GTO plus $15k/kg for a low-cost d-OTV to GEO.

b. Transportation costs are $15k/kg to GTO plus $40k/kg for a low-cost r-OTV to GEO. We have not explicitly calculated the cost for an r-OTV in GEO; we simply double the costs per kilogram compared to its use in LEO. For reference, this is the ratio we calculated for d-OTV costs in GEO to LEO.

We compare the costs of low-cost building blocks with the cost to beat and illustrate the break-even cases in Table 28. For a small satellite launched to GEO with a single instrument, we estimate that it would be cheaper for a payload owner to integrate their payload onto a modular bus prior to launch than to use a building block outpost. After a single technology refresh mission, the cost of using a stripped down building block outpost effectively breaks even with the cost of launching another small satellite to replace the old one. Approximately five technology refresh missions are needed before a fully equipped building block outpost breaks even with relaunching a new satellite for each technology refresh.

Table 28. Hardware Cost Comparison for Technology Refresh: Small Satellite at GEO

Scenario	Nominal Hardware[a]	Refresh[b]	Total (1x refresh)	Total (5x refresh)
Cost to Beat	$31	-	$62	$186
Building Block	$73	$22	$95	$183
Building Block Stripped-Down	$36	$23	$59	$151

Note: All costs in millions of U.S. dollars

a. Includes cost of launch to GEO.

b. Includes cost of launch to GEO. One low-cost instrument.

With a break even at about a single refresh for the stripped down outpost, it seems that there would not be a strong reason to use an outpost to mitigate a potential one-time failure. This assessment could shift in favor of the outpost if the cost to manufacture a second copy of the instrument were substantially cheaper than the costs of manufacturing the first. While the cost of manufacturing units tends to decrease in proportion to the number of units produced, scientific sensors are generally intended to be made only once. It is unclear what potential cost reduction, if any, is possible for manufacturing a copy of such a bespoke item. Our assessment could also shift against the outpost if the cost of using an r-OTV increases.

In the SpaaS paradigm, it would not take much more time to integrate a wholly new satellite on the ground than to integrate a new instrument into an orbiting outpost. A manufacturer may have one or two modular buses already on the shelf, allowing a SpaaS provider to readily purchase a new one in the event of a failure. If the instrument has to be made again, that will likely be the long lead item. Similarly, both an outpost and the alternatives still require a small launch vehicle, which will add to the lead times of both options approximately equally. Thus, there is unlikely to be a schedule benefit to use of an outpost compared to alternatives that refresh small satellites after failures.

A fully functional outpost—with a robot arm and RPO capability—would require five refresh missions to break even. In this case, an outpost might be competitive if wholly new instruments are flown every 1 or 2 years. Taking the instruments in the A-train for example, OCO-2 had a design life of 2 years, while all other instruments have design lives from 3 to 6 years. However, with a refresh rate of 2 years, a science campaign would only use 4 refresh missions over the course of a 10-year satellite bus. This is insufficient to meet the break-even usage rate.

In the above example, we used the lowest possible in-space transportation costs for the technology refresh. Thus, an outpost is not competitive compared to the cost to beat for higher costs of in-space transportation; hence, we do not consider them explicitly. As the launch cost for the nominal satellite or outpost falls, again the outpost becomes less competitive; for example, if all launch and in-space transportation services were free, costs would break even at eight refreshes and two refreshes for building blocks and stripped down building blocks, respectively. Thus, an outpost is not competitive for this application in LEO, where launch costs are less than for GEO.

2. For Large Satellites

We also analyze using an outpost to replace a larger satellite that can host six instruments. For the larger outpost, we use both scenarios of the CondoSat. The satellite is populated with two high-cost instruments and four low-cost instruments, as described in the previous section. For each scenario, we investigate two cases: a single high-cost instrument fails or all instruments need to be refreshed. The relevant costs used for the comparison are calculated in Table 29, using similar logic as for the small satellite case.

Table 29. Hardware and Launch Costs for Nominal and Single-Refresh Scenarios of a Small Satellite in GEO

Scenarios	Units	Unit Cost [$k]	Mass [kg]	Transport Total [$k]	Hardware Total [$k]	Total [$k]
Large Satellite – Cost to Beat[a]						
Large Bus	1	125,000	4,700	188,000	125,000	313,000
Low-Cost Instrument	4	20,000	50	8,000	80,000	88,000
High-Cost Instrument	2	250,000	175	14,000	500,000	514,000
Total						**915,000**
Condo Sat – High Traffic[a]						
Outpost Bus [Low Cost]	1	180,000	4,850	194,000	180,000	374,000
Low-Cost Instrument	4	20,000	50	8,000	80,000	88,000
High-Cost Instrument	2	250,000	175	14,000	500,000	514,000
Total						**980,000**
Condo Sat – Technology Refresh[a]						
Outpost Bus [Low Cost]	1	130,000	4,700	188,000	130,000	318,000
Low-Cost Instrument	4	20,000	50	8,000	80,000	88,000
High-Cost Instrument	2	250,000	175	14,000	500,000	514,000
Total						**920,000**
Refresh 1 Instrument with d-OTV[b]						
High-Cost Instrument	1	250,000	175	9,625	250,000	259,625
Total						**260,000**
Refresh 6 Instruments with d-OTV[b]						
Low-Cost Instrument	4	20,000	50	11,000	80,000	91,000
High-Cost Instrument	2	250,000	175	19,250	500,000	519,250
Total						**610,000**
Refresh 1 Instrument with r-OTV[c]						
High-Cost Instrument	1	250,000	175	41,125	250,000	271,875
Total						**270,000**
Refresh 6 Instruments with r-OTV[c]						
Low-Cost Instrument		20,000	50	47,000	80,000	127,000
High-Cost Instrument		250,000	175	82,250	500,000	582,250
Total						**710,000**

Note: All total costs (in bold) are rounded to 2 or 3 digits

[a] Transportation costs are $40k/kg directly launching to GEO using something like Falcon Heavy.

[b] Transportation costs are $15k/kg to GTO plus $40k/kg for a high-cost d-OTV to GEO.

[c] Transportation costs are $15k/kg to GTO plus $220k/kg for a high-cost r-OTV to GEO.

For these scenarios, use of an outpost is only marginally more expensive than integrating the satellite on the ground and offers substantial cost reductions for even a single technology refresh. Table 30 shows two possibilities: refreshing a single high-value instrument or refreshing all of the instruments onboard. If all of the instruments will be refreshed, the cost to beat is simply the cost of a completely new satellite. The table shows a cost savings of approximately $200 million when using an outpost to refresh the entire instrument suite. The costs for the CondoSats are calculated using the low-cost option for the outpost bus. Using the high-cost CondoSats would only add $130 million to the cost of the High Traffic Condo Sat—still leaving $70 million in savings for that scenario. On the other hand, we used high-cost values for in-space transportation of replacement instruments; if lower cost options for in-space transportation are available, that will further increase the cost savings of both outpost scenarios.

If only a single instrument fails and needs to be refreshed, the cost to beat is arguably the cost of mounting the new payload *on a smaller bus* and then co-orbiting the new satellite with the large one. However, we assume that the instruments on the original satellite have been designed to work together and, as before, the entire satellite would need to be replaced to fully repair the lost functionality. Table 30 shows that an outpost can achieve a cost savings of approximately $500 million in hardware and launch costs in the event of a single-instrument failure. The considerations previously discussed about the high-cost options for the outpost and the in-space transportation services also apply to this scenario.

Table 30. Hardware Cost Comparison for Technology Refresh: Large Satellite at GEO

Scenario	Nominal Hardware[a]	Refresh 1 Instrument[b]		Refresh All Instruments[c]	
		Marginal	Total	Marginal	Total
Cost to Beat	915	-	1,830	-	1,830
Condo Sat – High Traffic	980	260	1,240	610	1,590
Condo Sat – Technology Refresh	920	290	1,210	710	1,630

Note: All costs in millions of U.S. dollars.

[a] Includes cost of launch to GEO.

[b] Includes cost of launch to GEO. One high-cost instrument.

[c] Includes cost of launch to GEO. Two high-cost instruments and four low-cost instruments.

A major caveat to this result is that the trend for satellites is moving away from large, expensive satellites in high orbits and toward proliferated architectures in lower orbits that are tolerant to loss of a few nodes. Future satellite capabilities will be achieved using less expensive instruments integrated on cheap, mass-manufactured buses. The use of an outpost for technology refresh is thus relevant for the near term, but its attractiveness may deteriorate as science and defense users learn to design satellite architectures that follow the trend set by the commercial sector.

On the other hand, if in-space technology refresh becomes mature and relatively low cost, it may also incentivize satellite operators to continue using monolithic architectures. For example, our high-cost science instrument costs $250 million to develop, but if the payload owner had an easy option to refresh the instrument in the event of a failure, they could design the instrument less robustly and at lower cost. Further, if the payload owner was *planning* to refresh the instrument after a short period of time, they may be able to reduce costs even further by designing a campaign of relatively short-lived instruments, where each instrument is fairly economical to produce. For example, instead of spending $250 million on a single instrument that lasts 6 years, perhaps the payload owner could create three instruments, each designed to last only 2 years, for approximately the same budget. We do not analyze this possibility; thus, we cannot comment on its credibility.

A final observation is that the owner of this outpost could sell the entire outpost to another user. This would allow the initial user to recoup some of their costs if the mission is effectively over while the bus still has a few years of operational life. Likewise, the new user would be able to use the outpost as a bus with a substantial savings to their program. The case of refreshing all six instruments is illustrative. The cost of an empty High Traffic Condo Sat and its launch to GEO is approximately $370 million. If the bus is sold for half price, potentially after 5 years of its 10-year design life, the outpost may cost $185 million. The cost of purchasing and launching a non-outpost satellite based on the same bus (SSL 1300) to GEO would be approximately $310 million. Thus, a new program may be able to save around $100 million by using an old outpost instead of building and using a new bus.[24]

3. Potential Market for Technology Refresh

We have shown it is unlikely there will be a market for a small outpost to provide technology refresh capabilities in GEO. Since a small outpost is not economical in GEO, it would be less economical in LEO, where transportation costs are lower. Instead, we focus on the potential market for a larger outpost in GEO.

NOAA is the most likely client for this service. They require persistent coverage of the Earth for meteorology and Earth science measurements. Specifically, NOAA could

[24] The true savings would likely be less than this. If the payload owner has a mission that requires 5 years of operational life, they may not purchase a bus that is rated for at least 10 years.

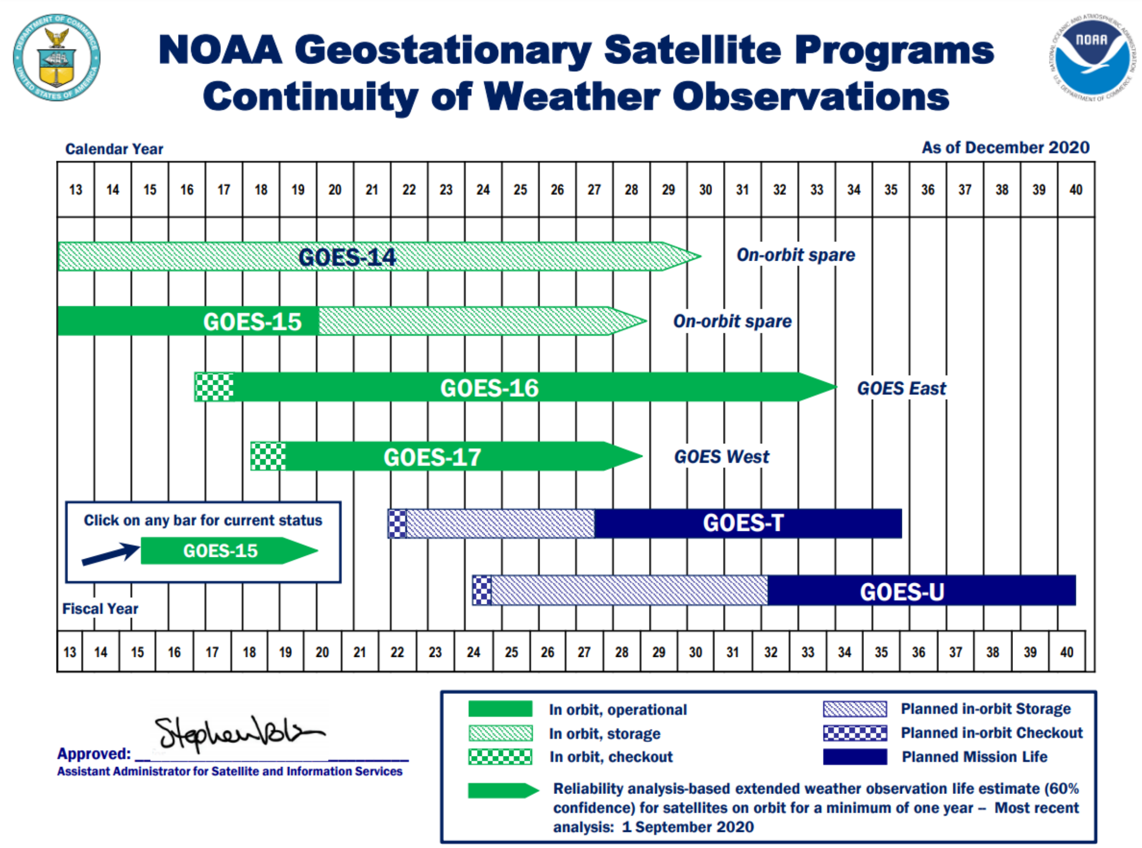
likely improve its operations by using an orbital outpost for its Geostationary Operational Environmental Satellite (GOES) satellites. The GOES satellites support critical services that cannot suffer an interruption, such as weather forecasting and monitoring of extreme weather. To ensure this capability is persistent, NOAA keeps at least one spare satellite on orbit that can cover for a full or partial failure of an operational GOES satellite (Figure 14).

Newer GOES satellites (16, 17, T, and U) have costs reasonably aligned with our large satellite example. In 2013, the Office of Inspector General (OIG) estimated that the full lifecycle budget "for four satellites, the ground system, and supporting operations through 2036" was likely about $12 billion in 2020 dollars (NOAA OIG, 3).[25] The satellite itself cost approximately $510 million, the Advanced Baseline Imager (ABI) instrument costs about $420 million, and the Geostationary Lightning Mapper (GLM) instrument costs about $100 million (NOAA OIG, 12).[26] The satellite also carries four other instruments that appear to be smaller and each cost in the low $10s of millions. Thus, comparisons between GOES satellites and the large CondoSat are reasonable.

NOAA could use an outpost to mitigate failure of the instruments onboard GOES satellites. For instance, the ABI instrument appears on all four of the new GOES satellites and it failed on GOES-17. To fix the issue, the ABI instrument had to be redesigned and the launches of GOES-T and GOES-U have been delayed while the instrument is being fixed; however, GOES-17 operates with degraded performance because there is no way to fix the instrument onboard. Had NOAA used an outpost for this series of satellites, they would have the opportunity to replace the faulty ABI on GOES-17 and be able to replace the ABI instrument on GOES-16 if that unit ever fails.

[25] The cost was given as $10.9 billion by the OIG in 2012 dollars and includes cost growth and cost overrun. We have inflated all OIG costs to 2020 dollars, using a factor of 1.136, and rounded them in main text.

[26] Specifically, the OIG reported the spacecraft cost $897 million for two buses. The ABI cost $746 million for two instruments. The GLM cost $247 million for three instruments.



Source: NOAA 2020b

Figure 14. Schedule of GOES Operations Required to Maintain Persistent Coverage

Using this capability, NOAA could potentially reduce its reliance on spare satellites. GOES-15 and 16 have design lifetimes of 15 years; however, each satellite will each be placed into storage mode for the final 5 years of its lifetime. Likewise, when GOES-T and U launch, each satellite will spend the first 5 years of its lifetime in storage mode, serving as backups for other operational satellites. Some satellites are never intended to enter into operations; the GOES-14 satellite was launched for the exclusive purpose to be a spare. If NOAA were able to schedule maintenance of its existing fleet such that it could forego extensive reliance on in-space spare satellites, the agency would likely save billions of dollars in reduced hardware and operations costs over the course of a 20-year program.[27]

We believe it is likely that NOAA would use an outpost for technology refresh in the event of an instrument failure; however, we are unable to assess whether NOAA would likely forego an in-space spare. We find it unlikely that NOAA would use a posture that repairs failures just-in-time. First, the outpost would have to restore capability on a

[27] Roughly estimating that a single satellite costs $3 billion over 20 years (this is the per-satellite cost for the current GOES series), that leads to an annualized savings of about $150 million per year.

timescale that is comparable to the use of an on-orbit spare. On-orbit storage allows for restoration of capability "in less than one week" and "avoids the chance of a launch failure when you can least afford it" (NASA 2009). Second, spare satellites undergo an extensive checkout process once they reach orbit; GOES-14 spent 6 months in checkout before it moved into a storage orbit. After integration of the new instrument on an outpost, the checkout time would need to be effectively eliminated to restore capability in a timely manner. While just-in-time repairs may not come to fruition, on-orbit repairs may allow for scheduling efficiencies among operational and spare satellites that could reduce the total number of spare assets needed.

Most missions in GEO—and some missions beyond GEO, such as at LaGrange points or in cislunar space—may also be potential users of a hardware refresh outpost, owned by the primary user. This includes meteorological missions for DoD; space weather missions for NOAA, NASA, and DoD; communications satellites for DoD and private industry; and more. We do not analyze these potential mission sets. We simply note that substantial revenues seem feasible for a wide variety of missions.

C. Microgravity R&D

Microgravity can be used as a research tool in numerous disciplines: materials science, ranging from metallurgy to colloidal crystals; chemistry, ranging from protein crystallization to flow chemistry; biology, ranging from botany to microbial research to tissue engineering; and physics, ranging from fluid physics to fundamental physics (Corbin et al. 2020). Research in microgravity removes many of the perturbing effects of gravity that can obscure more basic processes. Most prominently, microgravity removes the effects of sedimentation and buoyancy-driven convection (Chao et al. 2015). As a result, thermal gradients are more uniform and conduction is the driving heat transfer mechanism in place. The combination of these effects and others allow researchers to examine many phenomena and processes on a more fundamental level than possible in Earth's gravity, particularly on the nano- and meso-scale.

American efforts on the ISS have been led by NASA and, more recently, by the International Space Station National Laboratory (ISSNL). NASA-sponsored research is designed to support their mission of space exploration, and, as a result, heavily favors human research, space biology, fluid physics, combustion science, and fundamental physics. Conversely, ISSNL-sponsored research tends to focus on using microgravity and other aspects of the space environment for benefits on Earth. The majority (about 57%) of ISSNL research falls into the categories of industrialized biomedicine and advanced materials and manufacturing (ISSNL 2020).

Industrialized biomedicine is defined by the ISSNL as experiments that "enable biomedical advancements with a defined pathway for translation from scientific research to industrial or clinical applications," such as new therapeutics and procedures (ISSNL

2019). Within this area, tissue chips, organoids, rodent research, and macromolecular crystallography are seen as the most promising applications. These applications all represent efforts to use microgravity to create better biological models to study disease and design medical therapies. Research into tissue chips, organoids, and rodent research attempts to improve and supplement existing terrestrial models for drug development and design, particularly for degenerative conditions. Microgravity provides means to model various diseases associated with aging and with degenerative conditions. For macromolecular crystallography, microgravity can allow for large, well-ordered crystals to develop, and researchers can use this information to better understand the structure of a macromolecule of interest, which in turn can be used to inform the drug design process.

Advanced materials research refers to areas that benefit from the ability to produce materials in a form or purity that cannot be done terrestrially. Advanced materials manufacturing is often included with advanced materials research, but for the purposes of this report, manufacturing is discussed separately from materials research. Microgravity can allow commercial researchers to better understand the properties of material on a more fundamental level. The knowledge gained from these investigations is generally used to improve terrestrial manufacturing processes, not as a first step toward manufacturing the materials at scale in space.

For our analysis, we partition microgravity R&D into two categories. First, we examine microgravity R&D that requires down-mass capability to bring the results of the experiment safely back to Earth for analysis. Second, we examine R&D that can be performed completely remotely, without the need to return mass back to Earth.

1. R&D Requiring Down-Mass

The primary alternative to performing R&D that requires return mass would be to launch the experiments inside a returnable cargo capsule, such as the SpaceX Dragon, or a returnable spaceplane, like Dream Chaser or the X-37b. Likewise, each outpost scenario will also require the use of such a returnable cargo vehicle. Use of an outpost requires the user to cover the excess costs associated with robotic arms and extended spacecraft lifetimes. Alternatively, forgoing the use of an outpost requires the users to cover the costs of launching the lab hardware each time. The presence of this hardware in the cargo vehicle also displaces other potential paying customers, leading to fewer customers in the vehicle than if the vehicle were destined for an outpost. The potential for an outpost to outcompete the alternatives will be a balance between these excess costs.

We attempt to make our comparison regarding return mass to be somewhat comparable with our comparison of microgravity R&D that does not require mass by parametrizing the analysis in terms of the standardized units (U) typically associated with CubeSats and modular experiments on the ISS. Further, to reach substantial customer volume, experiments will likely need to be as cheap as possible; small, pressurized experiments are likely the most instructive example. For our comparisons, we assume that the payloads have been containerized into 1 U form factors.

The costs associated with 1 U microgravity experiments for 1 month and 24 months are calculated in Table 32. In the low-cost cases—i.e., high demand—the outpost scenarios are significantly cheaper than the cost to beat. The cost of transportation to the outpost is the driving factor. It may be possible to cut the cost of space transportation in half by using an orbital outpost; this is because roughly twice as many experiments can be loaded onto the launch vehicle if the transportation vehicle does not need to host the experiments—merely to transport them.

To achieve the low-cost outpost scenario, demand for microgravity R&D would need to be about four times what could be handled by the cargo vehicle scenario—3,240 U versus 810 U. With four times the customers all using the same platform, we expect the orbital outpost to experience enhanced schedule difficulties and degraded microgravity conditions compared to the cargo vehicle. This use case likely makes more sense for long-duration experiments, where the needed time in microgravity exceeds the orbital lifetime of a baseline cargo vehicle.

Per our calculations, a cargo vehicle may have hardware costs in the low hundreds of thousands of dollars per U. Further, both outpost scenarios seem able to achieve similar or lower cost points. When incorporating the other costs that we have omitted—due to their not being significant differentiators between scenarios—the price that microgravity R&D users pay will increase substantially. We do not estimate what the final price may be, but assume for the sake of argument that it is approximately a factor of two above the hardware and launch costs. Use of a cargo vehicle would cost well under $500k per U. Factoring in a few $100k for the design and operation of the experiment, the total cost of using a cargo vehicle for microgravity R&D would be within easy range of NASA's various microgravity related grants and would not necessarily require a subsidized launch. Likewise, a company could use its Phase I and II SBIR funding to support a 1U microgravity experiment.

Table 32. Cost Comparison for Microgravity R&D with Return Mass

Scenario [Cost Level]	Transport [$k/U]	Rent [$k/month]	1 Month Total [$k]	24 Month Total [$k]
Capsule Outpost				
Low Cost [a]	55	1.1	56	81
High Cost [b]	220	6.4	226	374
Module Outpost				
Low Cost [a]	55	.4	55	65

Scenario [Cost Level]	Transport [$k/U]	Rent [$k/month]	1 Month Total [$k]	24 Month Total [$k]
High Cost [b]	220	2	222	268
Cargo Vehicle – Cost to Beat				
Low Cost [c]	110	0	110	110
High Cost [d]	220	0	220	220

[a] Low-cost rent assumes 3,240 U of simultaneous customers. At this level, the delivery cargo vehicle will be packed full—1,650 U—allowing it to charge its low cost of delivery.

[b] High-cost rent assumes quarter usage—about 810 U of customers on the outpost. We assume the cargo vehicle that delivers payloads will only be able to fill itself to a quarter of its capacity—about 400 U.

[c] The low-cost outpost scenarios placed 1,650 U of experiments into a cargo vehicle for delivery at once. A cargo vehicle that hosts experiments—instead of just transporting them—can only hold 810 U maximum. Thus, we use the maximum usage cost.

[d] The high-cost outpost scenarios placed 400 U of experiments in a cargo vehicle at once. This is approximately half of the capacity that a cargo vehicle can host; thus, we use the cost associated with half capacity for this scenario.

Given that relevant cargo vehicle technology has existed for about 10 years and is likely to be affordable for potential users, why has this capability not been operationalized already? We see two main possibilities. First, the true cost may be more than a factor of two above the hardware and launch costs, putting it out of the range that could be easily afforded. This could be the case if issues related to scheduling and operating so many simultaneous payloads are prohibitive. Second, NASA's subsidies for microgravity R&D may be distorting the market. This interpretation is somewhat fraught, because the market would not exist if not for NASA as the almost exclusive source of demand for microgravity R&D in the United States. Regardless, it may be that there is not enough demand for microgravity R&D even at such a low cost. Both possibilities also apply to the use of an outpost; thus, it is difficult to see how such a system could reach the levels of demand required to cover costs. In this case, revenues for microgravity R&D on an outpost seem plausible, but it would likely require other lines of business on the same outpost to fully cover costs.

2. R&D That Does Not Require Down-Mass

There are two main differences between this use and the use case where return mass is required. First, the space vehicle carrying the payloads into space does not need to be a reusable cargo vehicle—any form of space transportation will suffice. Second, the main competitors for providing this service are small, disposable satellites. Small satellites have an established history of performing unpressurized experiments. They are increasingly performing experiments that require pressurized volume, such as the Eu:CROPIS experiment, which was a 250 kg satellite launched in 2018 to investigate plant growth in simulated lunar and Martian gravity. Pressurized microgravity can even be performed on

CubeSats, as recently demonstrated by SpacePharma's DIDO satellites, which are 3U in total size and provide about 2U of pressurized volume for experiments.

Table 33. Cost Comparison for a 2U Microgravity R&D Experiment with No Down-Mass

Scenario	Size [U][a]	Hardware Cost [$k] [b]	Transport [$k/U] [c]	Rent [$k/U/month]	12 Month Total [$k]
Building Block with RPO [d]					
Low Cost	2	160	22	2.7	270
High Cost	2	160	50	15	620
Building Block Stripped Down [e]					
Low Cost	2	160	50	0.63	275
High Cost	2	160	230	1.3	651
CubeSat – Cost to Beat					
Low-Cost Transport	3	210	22	0	276
High-Cost Transport	3	210	50	0	360

a. The number of U of spacecraft that must be launched. For a 2U experiment, only 2U needs to be launched to an outpost. A CubeSat requires at least 1U extra for a command module.

b. In Appendix A, we estimate that the cost of a CubeSat is $50k per U. Additionally, the cost of a 2U pressurized lab is $60k, which will be required in all scenarios. This column = $60k + $50k * Size.

c. We have previously shown that about 2kg of mass are launched per U when the mass of the deployment mechanism is included. For all scenarios, we multiple the relevant launch costs from Earth plus the d-OTV or r-OTV costs per kilogram by a factor of two.

d. Monthly low and high rents for a Building Block with RPO are $65k and $360k, respectively. Assuming those apply for experiments of 1 MLE in volume and that 24U fit in 1 MLE, we calculate monthly rents per U by dividing each rent by 24.

e. Monthly low and high rents for a Building Block Stripped Down are $15k and $30k, respectively. We divide by 24 to get the rent per U.

Table 33 shows the costs per U associated with a 12-month microgravity experiment. This experiment duration is approximately the break-even point for low-cost outposts; for experiments longer than 12 months a CubeSat is preferable, while experiments lasting less than 12 months are preferably hosted on an outpost. The difference between a low-cost outpost and a CubeSat for a 1-month mission (not shown) is only a few $10s of thousands. If the full costs of building and launching the experiment are factored in, the difference between the CubeSats and the outposts will be marginal. Thus, a low-cost outpost is likely to face stiff competition from CubeSats. A high-cost outpost is unlikely to be competitive, since both scenarios are nearly twice the cost of a high-cost CubeSat.

3. Potential Market for Microgravity R&D

The market for microgravity R&D is driven by expenditures by NASA, NASA funding for non-traditional users through the ISSNL, and other customers of the ISSNL (Corbin et al. 2020). By far, NASA is the largest single user of microgravity R&D and spends more than any other user, by type or by individual entity. We describe NASA and non-NASA demand for microgravity R&D, the pros and cons of using the ISS or its successor platform, and assess whether a niche exists for microgravity R&D hosted on an orbital outpost.

As outlined in Table 34, NASA expenditures in FY 2019 for all ISS research totaled \$429 million (NASA FY 2021 Budget Estimates). NASA's exploration-focused research comprises 61% of annual ISS research expenditures. Exploration-focused research on the ISS "supports the Agency's need for improved knowledge about working and living in space to enable future long-duration human exploration missions" (FY 2021 Budget Request). The remaining \$169 million represents NASA's expenditures on non-exploration focused research, which includes ground-based, free-flyer, and ISS life and physical science research that does not directly relate to NASA's human exploration mission. The funding is not all for microgravity research; for instance, the Alpha Magnetic Spectrometer (AMS) on the ISS and Multi-User Systems and Support (MUSS) programs are funded through this budget. ISSNL funding is part of the ISS non-exploration research budget.

Table 34. Research Budgets for the International Space Station

Budget Element	By Fiscal Year in Millions of Dollars			
	FY17	FY18	FY19	FY20
Exploration ISS Research	174	204	260	249
Non-Exploration ISS Research	204	143	169	155
ISSNL Subsidies[a]	7.3	5.5	4.9	4.7

Source: NASA FY2021, FY2020, FY2019 Budget Estimates; ISSNL Annual Reports

[a.] These subsidies do not include the value of the launch, which is also covered by NASA

Non-NASA expenditures in the microgravity R&D domain are smaller but still present. The end-users in this segment are commercial entities, non-NASA government agencies, academia, and non-profits. Over the 10 years of the ISSNL's operations, as directed by the Center for the Advancement of Science in Space (CASIS), about \$190 million in non-NASA, non-ISSNL investment has been made in microgravity (FY 2020 Annual Report). In this same period, ISSNL has facilitated about 520 experiments from non-traditional users (FY 2020 Annual Report).[28] This is approximately $19 million per year and $365,000 per experiment, on average.

Interviews have indicated that much of this investment is in-kind investment from the end-user—use of their own staff and resources for the experiment—rather than purely financial investment. Interviews with end-users for previous STPI projects have indicated an unwillingness to pay beyond current spending for microgravity experiments, unless the value proposition was to significantly change. Interviewees have also suggested that the average cost per experiment is around $600,000 to $700,000, which is absorbed by the ISSNL or NASA if not entirely covered by the end-user.

Current non-NASA demand for microgravity R&D is supported by NASA and ISSNL subsidies. Customers do not pay for launch costs, which are entirely covered by NASA for all ISSNL experiments. Without these subsidies, customers would be less likely to undertake R&D in microgravity. The demand for research on the ISS is limited by the configuration and challenges of conducting experiments on a human run space station, like the ISS. Despite limitations, however, demand for microgravity R&D is buoyed by NASA and the ISSNL, which consistently engage in outreach efforts to attract users.

The ISS and its successor platforms are attractive for microgravity R&D because they provide a human crew, who can help with experiments, and to this point in time, subsidized launch and crew time. However, the ISS has its downsides. As noted above, some experiments cannot be conducted on a human-occupied space station because of potential dangers to the crew or the disruption of microgravity from human activities on the platform. In addition, some researchers say NASA's Safety Standards are opaque, cumbersome and too limiting. The can require large amounts of paperwork to fly even simple samples, regardless of whether that same compound or sample had flown before and reviews can take weeks or even months. Some interviewees suggested that an outpost would provide a place to perform R&D that is too dangerous for a crewed platform. We note that the Cygnus capsule can already perform such research, for example, the Spacecraft Fire Experiment (NASA n.d.c). Likewise, any uncrewed platform could perform such R&D, not just an outpost.

The launch timelines for the ISS can be rigid and cadences slow or erratic. Since much of the cargo on resupply missions is dedicated to supplies for crew, the amount of cargo space available for experiments and other payloads can be limited. Further, there is a fixed number of cargo containers with temperature controls or power for transportation to the ISS; as a result, interviewees indicate there can be a backlog of experiments pending available modules or researchers may be forced to expend more funds to include power,

[28] Of these 520 experiments, some portion is remote sensing or technology development testing rather than pure microgravity R&D.

refrigeration, etc. in their hardware. There are also hidden costs associated with the unreliability of launch schedules. When launches "slip" or their schedules are unexpectedly pushed back, researchers may need to replenish or entirely replace their samples or supplies. This is especially true in biological research, as rodents may need replenished supplies for transportation, or a chemical or biological reaction may need to be restarted after a launch slip. The challenging timelines associated with using the ISS may push customers to use a more agile platform that allows for small tranches of experiments to be flown at regular intervals. Users would gain the most schedule flexibility and speed by integrating their payloads into small satellites that can launch on the next available flight.

Some interviewees suggested that defense users are less likely to utilize the ISS, as work onboard the ISS cannot be classified and the details must be shared with the ISS's partnering countries. However, DoD research does takes place on the ISS, particularly through partnerships with non-DoD entities. Likewise, DoD has the option of using the X-37B platform or small satellites if it wishes to perform research that is classified.

Despite the challenges of the ISS as a platform just described, an alternative platform has not yet developed and reached broad usage. Cargo capsules and small satellites appear to be a cost effective way of performing microgravity R&D that are likely affordable through awards from common research grants and contracts. We think the most likely reason these platforms have not gained prominence is that without NASA grants to support the development of the experiments and without substantial subsidies for the launch and operation of microgravity R&D, there would not be sufficient customers to cover costs of a larger platform like a cargo capsule. By extension, that implies microgravity R&D may not be a major source of revenues for an outpost. Small satellites capable of performing pressurized microgravity R&D are emerging and appear to have comparable costs to the use of an outpost; thus, an outpost will face stiff competition for revenues from any customers that do exist.

The best chance an outpost has of gaining microgravity R&D revenues is to be integrated into NASA's commercial LEO destinations program. By participating in a partnership with NASA's future crewed platform, an outpost owner would benefit from customers brought to its platform via NASA research grants and launch subsidies. NASA may benefit by having a more cost-effective method of performing microgravity R&D, thereby reducing the amount of subsidies that it must provide. Conversely, NASA could reduce the subsidies it offers—potentially increasing its microgravity R&D awards by the same amount—and letting the awardees pick their preferred platform based on cost, schedule, and performance characteristics of potential platforms. This would establish more of a market for providing microgravity services that industry could design future platforms to serve.

Similarly, NASA could cease to provide certain types of microgravity R&D services on the ISS or its successor platform, while committing to still fund such research.

Currently, NASA competes with industry to service microgravity R&D customers; by removing portions of this competition, customers and industry may shift to a more market-oriented approach. For example, any microgravity R&D that can be performed in a free-flying CubeSat is potentially not appropriate to be conducted on a government platform. Through coordination with researchers and industry, NASA could develop a plan for transitioning microgravity R&D services over to industry.

D. Manufacturing for Terrestrial Customers

1. Exotic Fiber Optic Cable

Conventional silicon optical fiber, which has a wide range of applications in telecommunications, computers, and servers, is subject to signal loss and is sensitive to radiation. Some alternative materials, such as ZrF4-BaF2-LAF3-AIF3-NaF (known by its trade name, ZBLAN), experience less signal loss and are less susceptible to heat and radiation than traditional cables. Because of these characteristics, ZBLAN is used for lasers for surgery, infrared countermeasures for military aircraft, and nuclear reactor testing equipment (Kasap 2018). Server farms could benefit from the increased potential for and accuracy of data transmission using ZBLAN (Cozmuta and Harper 2014).

To capitalize on the reduced signal attenuation of ZBLAN, long stretches of fiber could be used in telecommunications. However, ZBLAN fibers are weaker than their traditional optical fiber counterparts, so the reliability of very long lengths of fiber is uncertain. They could not currently be used for transcontinental or transoceanic telecommunications cables (expert interview). These uses of ZBLAN are currently limited by the scarcity of high-quality ZBLAN and price.

Although ZBLAN is manufactured on Earth, the purity of the crystals in the fibers is limited by gravity-induced convection and the non-uniform distribution of chemicals during the production process. These limitations cause crystals to form in the fibers before the glass can cool. ZBLAN fibers processed in microgravity have better clarity, reduced signal attenuation, and a bandwidth for transmission that extends into the infrared (Torres, Ganley, and Maji 2014). Because crystals begin to grow at higher temperatures in a microgravity environment than on Earth, manufacturers also have a wider working temperature range over which the glass can be drawn into fiber. There is no known method to produce ZBLAN that suppresses crystallization during the fiber-drawing process other than the use of microgravity.

Three companies have successfully demonstrated production processes for manufacturing ZBLAN on the ISS: Made in Space, Fiber Optics Manufacturing in Space (FOMS), and the Physical Optics Corporation (POC). FOMS validated its suitcase-sized fiber drawing system in 2019 (Werner 2019). Made in Space has produced fiber using its microwave-sized machine several times (Wall 2019). Made in Space and FOMS have reported that their systems have yielded fibers of higher quality than can be produced on Earth (Kasap 2018.) An earlier, experimental prototype was 12 inches in diameter, 40 inches in length, and weighed less than 100 pounds.[29] It ran on an internal battery, was controlled by a laptop, and successfully pulled ZBLAN cable from preform during a parabolic flight. FOMS states that its system will yield 50 kilometers of fiber per mission using its patented Space Facility for Orbital Remote Manufacturing (SpaceFORM) (Kasap 2018.) As of this writing, POC has not publicly released results of its flight experiment.

All of the processes begin with a preform as the material input. The cylindrical preform can be heated using a laser, heat gun, or oven. The softened material is then drawn into a fiber that is wound around a spool, which applies torque to continuously draw the fiber. By changing settings, such as the temperature of the preform, the speed of rotation of the spool, and the tension applied to the fiber, the properties of the resulting optical fiber can be adjusted and controlled. These operating parameters may be controlled remotely, programmed in sequence, or implemented using automated controls that refine the process in real-time. Sensors can measure the fiber diameter, detect crystallization within the drawn fiber, and take other measurements that provide feedback to the control system. The spool of optical fiber may be transported back to Earth shortly after it is processed or stored for future transport.

An orbital outpost would have to provide an internal space for the machine to operate, sufficient power to heat the preform and operate the equipment, thermal management, and the ability to move the materials and machinery. We assume a payload created for an orbital outpost would be similar in size to FOMS suitcase-sized fiber drawing system or Made in Space's microwave-sized machine (Werner 2019; Wall 2019). Both companies have stated that they intend to achieve production volumes with machines of this size. On an orbital outpost, a robot capable of pulling the fiber would be needed to turn on and pull fiber (expert interview). According to one engineer, heating, slow cooling, and the working robot would require about 250 watts of power (Starodubov et al. 2014).

Small lengths of up to 2 meters of high-purity ZBLAN can be produced in the 20 seconds of microgravity provided by parabolic flights. According to an interviewee, these lengths are sufficient for use by the biomedical industry, but not by the telecommunications industry (Torres, Ganley, and Maji 2014). We use this rate for our analysis; ZBLAN fiber can be pulled at 160 kilometers per month.[30] Made in Space is experimenting with

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[29] We use this as our assumption for the volume of the fiber puller: 12" x 12" x 40" = 5760 cubic inches ~ 0.095 cubic meters. Likewise, the mass of the unit is 100 lb. = 45 kg.

[30] I.e., (2 meters/20 seconds) * (1km/1000 meters) * (86,400 seconds/1 day) * (30 days/1 month). Note that since 1 kg of preform makes 1 km of ZBLAN, the manufacturing rate is also 160 kg per month.

manufacturing ZBLAN on orbit. It claims that it will be able to produce 4 kilometers of optical fiber from 4 kg of preform (Wall 2017).

We first investigate the manufacture of ZBLAN on a reusable cargo capsule. Table 35 shows the total cost of buying a cargo capsule and launching it five times, each time with the suitcase-sized manufacturing equipment and all preform contained inside. We assume that the density of the preform is great enough that use of the cargo capsule is not volume constrained; thus, the relevant constraint is the capsule's down-mass. Thus, after loading the manufacturing equipment, the rest of the launched mass is preform and packaging (e.g., spools to hold the preform and finished product).

Table 35. Hardware and Launch Cost Comparison for Manufacturing ZBLAN inside a Capsule

Cost Element	Units	Unit Cost [$M]	Total [$M]
Launch	5[b]	50	250
Capsule	1	200	200
ZBLAN Machinery	1	10[c]	10
Monthly Rent	-	-	-
Total			**460**

Performance Variable	Mass [kg]	Length [m]
Cargo Vehicle [Down-mass]	3,000	
ZBLAN Machinery	100[d]	
Preform and Packaging per Launch	2,900	
Preform per Launch	2,610[a]	
Preform, Total Launched	13,050	
ZBLAN Returned		13,050,000

Cost of Product Due To Hardware and Launch	Average Cost [$/m]
Total	**35**

Note: We do not account for the cost of the preform

a. We assume that packaging materials account for 10 percent of the mass budget available for the preform. It will take about 10 months to pull all of this preform into ZBLAN at a rate of about 10 seconds per meter.

b. The cargo capsule is assumed to be used 5 times before it is retired.

c. We have no firm basis for the cost estimate of the machinery; however, it is irrelevant for a comparison with the outpost scenario. In this and the outpost scenario, only a single ZBLAN machinery unit is purchased, so it does not contribute to a cost delta between the two scenarios.

d. This is more than double the mass of the prototype machinery discussed earlier.

We also investigate the scenario where an outpost is used to manufacture the ZBLAN. The main difference in this case is that the machinery for producing the ZBLAN is launched into space only once and left there to be reused. This avoids the cost of repeatedly launching the hardware and also frees up mass in the cargo capsule to fly more preform, which in turn creates more final product. Another significant difference is that the outpost charges the ZBLAN producer rent for every month spent on station. We estimate the cost of using an orbital outpost to produce ZBLAN over the course of five launches—the same as in the scenario that did not use an outpost—in Table 36.

Table 36. Hardware and Launch Cost Comparison for Manufacturing ZBLAN inside a Traditional Module

Cost Element	Units	Unit Cost [$M]	Total [$M]
Launch	5	50	250
Capsule	1	200	200
ZBLAN Machinery	1	10	10
Monthly Rent	50[a]	0.58[b]	29
Total			489
Performance Variable	**Mass [kg]**		**Length [m]**
Cargo Vehicle, Down-mass	3,000		
ZBLAN Machinery, Mass	-		
Preform and Packaging per Launch	3,000		
Preform per Launch	2,700		
Preform, Total Launched	13,500		
ZBLAN Returned			13,500,000
Cost of Product Due to Hardware and Launch			**Average Cost [$/m]**
Total			**36**

Note:

a. It will take about 10 months to pull all of the preform into ZBLAN at a rate of about 10 seconds per meter. Assuming perfect scheduling efficiency over 5 launches will require spending 50 months on the outpost. We use five launches because that is the expected lifetime of the delivery capsule and was used for the previous scenario.

b. This is the low-cost rent for a traditional module outpost.

While our analysis suggests that ZBLAN produced on an outpost is more expensive than if it were produced on an alternative platform, the cost difference between the two options is likely within our margin error. Both options are equally competitive in effect. This is partially because the ZBLAN production machinery is a small fraction of the mass and volume budgets of the cargo capsule. Offloading the machinery to an outpost does not allow a substantially greater amount of preform to be flown to justify the cost of using the outpost. In our analysis, we assumed the machinery has a mass of 100 kg, which is approximately twice the mass of the relevant prototype machinery; the mass of the hardware would need to exceed 220 kg for the outpost to break even compared to the cost per meter of ZBLAN produced in a capsule. Our analysis has assumed that operations are mass constrained. Assuming that operations are volume constrained produces similar results; an outpost would face stiff competition from reusable capsules. Our analysis used the low-cost rent for a traditional module outpost. High-rent outposts would not be competitive.

Commercially produced prices for ZBLAN are reported to be in the range of $150 to $300 per meter (FindLight 2020). If the supply of high-quality ZBLAN increased and prices fell, demand should be strong for the uses listed above. Even if prices decline, manufacturing ZBLAN in space holds promise of being profitable. However, such profits are not likely to be captured by an outpost.

2. Biological Products

Some companies have proposed to use microgravity to produce various biological products. These biological products would be produced on an orbital platform and then transported back to Earth for commercial sale—not research. Retinal implants, large batches of stem cells for personalized medicine, and 3D printed human organs are a few products that are being actively explored. For our analysis, we focus on the latter product as it is likely to have a large amount of associated hardware that could be hosted on an outpost.

Credit: Techshot 2020

Figure 16. 3D BioFabrication Facility Developed by Techshot Launched to the ISS in July 2019

The cost of an organ transplant is significant. Despite the organ itself being "free," as they are donated rather than manufactured, there are substantial costs throughout the organ transplant process. Advocates for in-space bioengineering believe that 3D bioprinted organs will be competitive because, by using a patient's own cells to produce a biostructure, the patient would require less immunosuppressing medications. In addition, the ability to manufacture organs would reduce wait times.

To analyze this use case, we investigate the costs associated with two scenarios: manufacturing organs inside a cargo capsule and manufacturing organs on a traditional module outpost. For the cargo capsule, we use a capsule based on the SpaceX Dragon; however, we note that other companies, such as Space Tango, are considering the development of smaller capsules for the purpose of biological production. Unlike the previous analysis, we assume that organ-printing operations are volume constrained because each organ will likely require its own printing apparatus to minimize the time the printed organs spend on orbit.

Photographs of the 3D BioFabrication Facility (BFF) for the ISS seem to indicate that a single printer platform requires about 4 MLE of volume (Figure 16). To estimate the cost of printing organs in space, we construct an artificial operational scheme based on the BFF. We have not spoken with representatives from Techshot or NASA about the BFF facility; the following assumptions are completely our own for the sake of analysis. We assume that a print facility optimized for organ production will only require 2 MLE of volume to print an organ. One MLE of volume will house the electronics, printer heads, and other hardware required to perform the print. The second MLE of volume will be a hot-swappable cartridge that houses the print platform and preform materials[31] used for the manufacture of a single organ. The cartridge will also safely return the printed organ to Earth.

To produce organs inside a cargo capsule, the entire volume of the capsule would be filled with the production machinery previously discussed. Prior to each launch, a human would insert the cartridges into the capsule. After the organs are printed in space and returned to Earth, a human removes the cartridges containing the organs. The cost of producing organs in a cargo capsule is shown in Table 37.

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[31] The heart of a human male, which is larger than a female heart, has an average mass of 331 g and a standard deviation of 56.7 g (https://pubmed.ncbi.nlm.nih.gov/22182983/). This mass of preform should easily fit inside a 1 MLE cartridge.

Table 37. Contribution of Hardware and Launch Costs to the Price of an Organ Manufactured in a Reusable Cargo Capsule

Cost Element	Units	Unit Cost [$M]	Total [$M]
Launch	5	50	250
Capsule	1	200	200
Printing Machinery	27	10	270
Total			**720**
Performance Variable	**MLEs**		
Cargo Vehicle	54		
Machinery per Organ	2		
Organs returned per Launch	27		
Organs returned Total	135		
Cost of Product Due To Hardware and Launch			**Average Cost [$M]**
Total			5.3

To produce organs on a traditional module outpost, we assume that the first launch of the cargo capsule will carry only the needed machinery to print organs. Subsequent launches will carry a full load of the hot-swappable cartridges and preform that can print one organ each. A robotic arm will transfer the cartridges from the cargo delivery vehicle to the outpost for manufacturing of the organs, before being transferred back to the cargo capsule for return of the organs to Earth. Similar to the first launch, the final launch to the outpost does not manufacture any organs, but transfers the manufacturing equipment into the cargo capsule for return to Earth or disposal. This is to make room for new customers on the outpost.

As a rough assumption, we assume that five launches can occur in a single year. More frequent launches may be possible, but there will be time spent on maintenance of the cargo capsule, scheduling the launch, and integrating the genetic materials from the various customers into the cartridges. In addition, we have not fully accounted for the power requirements of printing so many organs at once. It may not be possible to manufacture all organs simultaneously; the organs may need to be printed in multiple batches per mission, which will increase overall mission timelines. We assume that operations continue for 5 years. Costs associated with this scenario are in Table 38.

Table 38. Contribution of Hardware and Launch Costs to the Price of an Organ Manufactured in a Traditional Module Outpost

Cost Element	Units	Unit Cost [$M]	Total [$M]
Launch	25	50	1,250
Capsule	5	200	1,000
Printing Machinery	54	10	540
Rent	60	3.9[a]	234
Total			3,024
Performance Variable	**MLEs**		
Organs Returned, First Launch	0		
Organs Returned, Last Launch	0		
Organs Returned, Intermediate Launches	54		
Organs Returned, Total	1,242		
Cost of Product Due to Hardware and Launch			**Average Cost [$M]**
Total			2.4

[a] This is the highest possible rent we calculated for a traditional module outpost. Lower cost rents do not significantly reduce the cost per organ and do not change our assessment.

We find that at an orbital outpost can potentially produce organs ($2.4 million each) at approximately half the cost of producing them in a reusable capsule ($5.3 million each). The true cost of producing each organ may be double or triple the costs associated with just the hardware and launch, for a total cost in the range of $5–$10 million.

Current terrestrial research, however, may undercut the need to produce such biostructures in space. Terrestrial research has seen significant progress in recent years. Most recently, 3D printed ears, bones, and corneas have entered clinical testing (Yasinski 2020). Dr. Anthony Atala of the Wake Forest Institute for Regenerative Medicine stated that while more complex solid organs may be years away from human trials, skin and blood vessels have already successfully completed human trials and will be used in clinics within the next few years (Kelly 2020). There are efforts from a number of universities and private companies developing 3D printed esophaguses, lungs, hearts, muscles, livers, kidneys, muscles, and ovaries (Yasinki 2020). Stomachs, intestines, and brain tissue are also under development but further from clinical use (Yasinki 2020).

A potential benefit for organs produced in space is that the microgravity environment may improve existing processes, as the weightlessness may allow for improved vascularization and "gray space" within the biostructures. For biostructures like hearts, creating blood vessels and capillaries remains one of the biggest hurdles terrestrially, and some believe microgravity may be a solution. Terrestrial researchers, however, have made progress in using hydrogels and collagen "skeletons" from donated organs as scaffolding (Montalbano 2021).

Terrestrial efforts to develop these products are more advanced than space-based technologies, and terrestrial efforts will continue to outpace those in space due to the limitations of current flight schedules. Flights to the ISS are limited to less than a dozen a year, and the throughput is such that a small number of experiments can be conducted a year, with a timeline of 2 years from submission to the ISS to flight. When other platforms become available, it is possible that the timelines for developing these products will accelerate, but until that time, terrestrial efforts will continue to develop at a pace faster than space-based efforts. Considering the pace of terrestrial research, organs produced on Earth may reduce or eliminate the need for in-space production.

For the sake of argument, let us assume that some high-value organs cannot be produced satisfactorily in terrestrial facilities. Would the market demand organs at the costs we have estimated for in-space production? Table 39 shows the estimated lifecycle costs associated with various organ transplants. It demonstrates that the cost driver for heart and lung transplants is the patient's admission to the hospital. The 180 days of post-transplant care are the second largest cost element, though it is a distant second. Procurement of the organ itself is not especially costly. One of the advertised benefits of using a 3D printed organ made from the patient's genetic material is that the costs of post-transplant care can be reduced significantly. This is not a convincing economic argument. Our estimate of the cost of a heart printed in space is many times greater than the entire lifecycle cost of a heart transplant. Even if the cost of hospital admissions and post-transplant care go to nearly zero, the use of a space-manufactured organ would still be many times more costly than the alternative.

Table 39. Costs Associated with Various Organ Transplants

Cost Element [$k]	Heart	Lungs (both)	Kidney	Liver	Pancreas
Medication While Waiting for Organ	36	40	29	31	22
30 Days Pre-Transplant	50	45	33	46	18
Procurement of Organ	130	130	110	100	110
Hospital Admission	1,100	760	150	490	150
Physician During Transplant	110	77	26	59	24
180 Days Post-Transplant Discharge	270	230	86	140	78
OP Immuno-Suppressants & Other Rx	40	55	32	38	27
Total	1,700	1,300	470	910	430

Source: Bentley and Ortner 2020; National Foundation for Transplants

Healthcare costs, however, are highly inelastic in that individuals are willing to spend what they must to address health concerns. Should bioprinted organs prove to be of higher quality, patients may elect to use them regardless of costs. In addition, the wait times for donated organs and tissues can be long, with many patients dying while still on the waitlist. In the United States alone, there are 107,000 people waiting for a transplant, as of January 2021 (HRSA 2021). We note that wealthy individuals may be willing to pay these higher costs as the alternative is death. More broadly, a robust market could emerge if insurance companies are willing to cover the costs associated with organs produced in space.

3. Semiconductors

Silicon carbide (SiC) wafers and semiconductor crystals could benefit from being manufactured in microgravity in space. SiC wafers can be used to manufacture computer chips that can operate in extreme heat. These wafers are considered to be of superior quality compared to the silicon dioxide wafers used to make traditional semiconductors (Crane et al. 2017). These SiC wafers can also withstand high amounts of radiation. By avoiding sedimentation, microgravity makes possible the manufacture of higher quality SiC wafers than is possible under Earth's gravity. Microchips made from SiC wafers reduce the need for heat sinks. These wafers have potential applications in electric and hybrid vehicles, solar arrays, power grids, and wind turbines (Crane et al. 2017). Because similar improvements in the quality of SiC wafers can be achieved using parabolic flights, which are much cheaper than the cost of launch to space, the current business case for refining these wafers on orbit has not been borne out.

Semiconductors manufactured under microgravity show greater promise. Terrestrial semiconductor chip manufacturing suffers from convection, sedimentation, and temperature gradients, consequences of Earth's gravity. These deficiencies could be allayed if the chips were manufactured in microgravity. The use of microgravity to manufacture higher quality semiconductors is being explored by various organizations. Made in Space, in particular, was recently awarded grants by NASA to investigate this potential (NASA 2020). Proponents generally focus on gallium nitride (GaN) semiconductor crystals, which are used in electronic vehicles, chemical sensors, and military radars. Producing higher quality GaN crystals could be of great value by enabling the production of more energy efficient chips that have improved heat resistance compared to more traditional semiconductors (Space Commerce Matters 2020). Older experiments have focused on gallium-arsenide, most prominently Alex Ignatiev's Wake-Shield experiments that produced semiconductors of 10,000 times greater quality than those made on Earth (Rosenblum 2017). Currently, experiments on semiconductor crystals in general have been focused on exploring the potential of microgravity. However, it is unclear whether production processes are scalable. Indium iodide crystals have greater potential, as they inhabit a specialized niche. These crystals are used by the Department of Homeland

Security (DHS) and the Department of Energy (DOE) to detect nuclear radiation (Molar-Candanosa 2017). Both DHS and DOE have funded microgravity research to explore the possibility of making superior indium iodide crystals and the theoretical limits of their radiation detection capabilities.

We do not analyze the use of an outpost in depth for this application because interviews indicated—and we concur—that this activity is unlikely to be technically suitable for an orbital outpost. The creation of high purity semiconductors in space requires near-perfect vacuum and will likely use a wake-shield to achieve the desired vacuum level. As such, sources of vacuum pollution are undesirable. Other customers on the orbital outpost, who do not have such strict vacuum requirements, may "outgas" volatiles from their payloads, polluting the vacuum. Likewise, the outpost itself may pollute the vacuum due to its materials outgassing or any stored volatiles used for thermal management or station keeping. The presence of orbital transfer vehicles coming and going from the outpost are another source of pollution. It is likely that the most appropriate platform for this activity is a custom-built, returnable vehicle (a capsule or spaceplane) that is able to control all aspects of its vacuum environment.

4. Potential Market

We have investigated only a few of the most promising potential products that might be manufactured in space. The three examples chosen reasonably span the space of possible manufacturing scenarios. We are unable to estimate potential revenues for any of these examples. In each case, outposts were not the cost-effective option *and* were unable to provide the product at a cost the market is likely to bear.

Our analysis of ZBLAN shows that for products that do not require a large amount of mass or volume to host the production machinery, an outpost is no better or worse than alternative methods of production. In this regime, an outpost may capture revenues if it can offer services that are more attractive than its competitors provide; however, interviews suggest that an outpost will not be the preferred platform. Machinery hosted in a returnable platform, like a capsule, can have regular maintenance applied after every use by crews on the ground; machinery hosted permanently in-space will have to be more robustly designed as it will not be easily serviceable.

We find that products requiring large volumes or masses of machinery to produce are good candidates for use on an outpost, such as printing human organs. Despite the high cost of the product, consumers may be willing to pay for the organs if terrestrially manufactured organs cannot be created satisfactorily. We note that the cost of organs printed in space could be substantially reduced if more organs could be transported back to Earth in the return capsule. However, to the extent that the production machinery can be made more efficient—i.e., reduced mass or volume of the equipment—the cost advantage of using an outpost decreases compared to using an alternative platform.

Some products, such as semiconductors, will have niche production needs that may provide incentives against using a shared or persistent platform. We only examined semiconductors, but other potential categories that might fit this model are those that are hard to automate or that must be brought down from space immediately after being manufactured there. The latter consideration might apply to many types of biological products, including 3D printed organs and artificial retinas.

E. Other Services

We were unable to analyze all of the potential use cases for an orbital outpost with our methodology. However, the remaining use cases are important and deserve to be discussed. The follow sections provide our partial assessments for other potential uses of an outpost.

1. On-Orbit Manufacture and Assembly of Space Assets

Satellites and other spacecraft are currently designed and manufactured on Earth and launched into space fully assembled. Because satellites have to survive the vibration and acceleration of launch, they have to be designed robustly and vigorously tested, adding to costs. They are constrained in size and architecture because they have to fit inside a launch vehicle fairing. They also incorporate a substantial amount of redundancy, in part because of the possibility that components will be damaged during launch. These constraints add costs and limit the capabilities of a satellite or spacecraft (Crane et al. 2017).

If assembled or constructed in space, structures such as antennas, solar panels, and long booms to isolate instruments could be designed differently, using larger sections and lighter structures, reducing construction and launch costs, and enhancing their utility. With assembly in space, structures can be packed into smaller, more secure packages for launch. If these structures were to be assembled on orbit, some of the costs of engineering, the number of redundant systems, and the expense of added robustness could be avoided or reduced. In particular, structural mass only required for the first 10 minutes—the launch phase—of a satellite's potentially 20-year lifetime could be eliminated (Crane et al. 2017).

Satellites or other structures assembled in space could be constructed so that they are larger and more capable than if assembled and launched from Earth. Telescopes with larger apertures than would be possible to launch from Earth could be assembled in space. They would provide improved observing capabilities and thus greater potential for scientific discovery (Clery 2016). Telescope components could be sent to orbit on lower-cost commercial launch vehicles and assembled on orbit, making a much larger aperture possible. Mirrors could also be lighter if they were launched without being folded in place and then assembled into a telescope in space, which in turn would reduce the need for packaging to protect the telescope during launch. Because the James Webb Space Telescope has yet to be launched, funding for another, more capable space telescope in the near term is uncertain. Although it would be advantageous to assemble the next large space telescope on orbit, we concluded that the next such project would be unlikely to begin within the period of time assessed by this report.

Communications satellites in GEO and large military and intelligence satellites could be candidates for on-orbit assembly (Crane et al. 2017). However, over the past few years, the market for large telecommunications satellites in GEO has deteriorated due to declines in subscriptions for direct broadcast TV and increased competition from fiber optics. Advances in miniaturization of components and other technological improvements have made on-orbit assembly for civilian satellites in GEO less attractive. This has left the potential market slanted towards military and intelligence satellites. According to one consultancy, the DoD and the U.S. intelligence services may purchase 23 satellites over a decade to be placed in GEO, or 2.3 a year (Euroconsult 2014b). It is not clear that assembling roughly two satellites a year would cover the capital costs of orbit assembly. The commercial space robotics market, for which OSAM activities are a large contributor, is forecast to generate global revenues in excess of $4.5 billion in the next 10 years (Werner 2020a). Needs for different orbits would make it necessary to use another spacecraft to move the assembled satellite to its preferred orbit, increasing costs. Competing platforms could create supply chain issues.

Assembling satellites or a telescope with a much larger aperture on orbit should be feasible on an orbital outpost. The building block with RPO scenario would be most appropriate and would function somewhat similar to the application demonstration activity. A platform and the equipment for assembling satellites or a telescope in LEO would need to incorporate many features of satellite or telescope manufacturing facilities on the ground, including testing equipment, assembly support, and warehousing (expert interview). During on-orbit assembly, components would need to be protected from collision with meteorites or other particles, temperature changes, atomic oxygen, radiation, and other qualities of the space environment that do not exist or are more easily controlled on Earth.

To assemble satellites in space, the alternatives to an orbital outpost are using a stand-alone platform dedicated to robotic assembly or continuing to assemble satellites on Earth. A dedicated platform has the advantage of avoiding leasing costs and of designing the platform for the sole purpose of assembling satellites. The orbital outpost provides the advantage of potentially more frequent delivery of components and modules in conjunction with delivery of other payloads to the orbital outpost and of reduced costs for the platform, as once assembly is completed, the user would no longer need to maintain the platform.

The comparative costs of assembling satellites on orbit as compared to terrestrial depend on the costs of the platform, robotic assembly, and transferring the assembled satellites from the platform to their final orbit. In a previous study (Crane et al. 2017), STPI concluded that for lower cost satellites in LEO terrestrial assembly is likely to be cheaper and more convenient than on-orbit assembly. Consequently, orbital outposts in LEO might not meet the needs of enough customers to be sustainable as a private endeavor.

2. Parts for Crewed Platforms

Human missions can save mass by bringing raw materials to space and using 3D printers to make parts and tools. For example, Made in Space installed a 3D printer on the ISS in September 2014, as part of its "3D Printing in Microgravity" experiment and has printed several tools (Kenna 2016). Using 3D printers reduces the need to stock missions with large numbers of spares, as only the raw material, which can be used for a range of parts and tools and the software to print it are needed. Obsolete and broken parts and components can be recycled and used as material for other additively manufactured parts, permitting savings in mass by repurposing these materials and upgrading components as time goes by. Structural components for objects in space could potentially be built in space without the need for an additional launch (Crane et al. 2017).

Currently, the market for parts manufactured in space is confined to the ISS. These parts could be manufactured on an orbital outpost, but would then have to be transferred to the ISS. Currently, the 3D printer on the ISS is booked for the next 6 months (expert interview). Demand may remain at this level for the life of the ISS. One printer is assumed to have the capacity to produce one job per day, on average (expert interview). Thus, the current market may be 365 jobs per year.

Made in Space and its partner, Lowe's Innovation Labs—a division of Lowe's, the hardware and construction materials retailer—installed a permanent 3D printer called the Additive Manufacturing Facility (AMF) on the ISS on March 26, 2016 (Kenna 2016). The printer is being used to manufacture small connectors, replacement components, and broken parts of scientific equipment. The printer can use 30 polymers, including the plastics ABS, HDPE, and PEI/PC. This capability is expected to expand in the near future (expert interview).

Unless demand other than the ISS emerges for parts in space, it is difficult to envision an orbital outpost being able to compete with a 3D printer installed on the ISS. The additional costs of transferring the component to the ISS would preclude any potential cost savings from using an orbital outpost.

3. Home Base for Robotic Servicing Vehicles

The outpost might be a temporary destination for a long-lived robotic servicing vehicle (RSV). Such vehicles could be used to provide life-extension services to satellites, perform replacements or repairs on existing operational satellites, provide general tug services (an r-OTV), or perform active debris removal. A relationship between RSVs and a persistent platform might be mutually beneficial. The RSV will likely need to replenish some consumables, which could be cached on the outpost for future use. These consumables could be launched just-in-time, without using an outpost as an intermediary; however, there is likely an economy of scale for delivering a large quantity of consumables at once, then allowing the RSV to periodically refresh its consumables as needed. Likewise, while the RSV is not servicing its own customers, it might dock with the outpost and augment the power, communications, or robotic manipulation services the outpost can offer to its customers. We briefly discuss three types of RSV services that may benefit from an outpost.

a. Life Extension Services

Satellites in GEO are designed to provide communications and other services to users for two, potentially three, decades. The end of these satellites' service lives is primarily determined by the point at which they run out of fuel. If the lives of these satellites could be extended, satellite operators would benefit from cost savings, as they could delay the purchase and launch of replacement satellites.

The current generation of GEO communications satellites is nearing the end of its lifetime. The launch of very large constellations of communications satellites in LEO and continued growth from terrestrial 5G services is greatly increasing competition for telecommunications services from GEO. Satellite communications operators are hesitant to make new investments in satellites in GEO in this market, but as current satellites run low on propellant to maintain their orbits, life extension services may become attractive so as to allow operators to delay their decisions to purchase a new satellite and wait for more certainty without losing revenue. However, satellites do become technologically obsolescent, so there are only a limited number of years where life extension is commercially attractive. Northern Sky Research (NSR) estimates that demand for life extension services in GEO could be up to 75 satellites through 2030, with a market opportunity of about $3.2 billion (Rainbow 2021).

The RSV providing life extension services will likely want to refuel on orbit and an outpost may be a valuable place for it to cache propellant. This is different from a propellant depot in that the propellant would be cached for use only by the RSV—the propellant containers would not be designed for more general usage by other customers. To service its satellite customers, the RSV may require spare parts, specialized tools, and custom adapters for docking that could be cached in space. The RSV operator may order the supplies necessary to service multiple customers to be delivered in a single launch to an outpost. The alternative to an outpost is to use a d-OTV for hosting propellant and spare parts. For rapidly used consumables, hosting them on a d-OTV may be the better option. Something like a stripped down building block outpost may find a niche where the materials must be cached for periods of time longer than the lifetime of a d-OTV—for example, consumables that will be resident in space for years or hosting a "toolbox" that is visited between every customer.

b. Debris Remediation

An RSV could perform debris remediation by either removing pieces of debris from the space environment or assisting satellites in implementing their post-mission disposal plans so that they do not go on to generate debris. There are more than 20,000 pieces of debris larger than 10 centimeters in diameter and roughly 500,000 pieces of debris 1 centimeter or larger in diameter orbiting Earth, mostly in LEO. There are millions of other pieces of debris too small to track (NASA 2013d). Large amounts of orbital debris pose a serious hazard to satellites, capsules, space stations, and people in space. In 2009, the Russian satellite Kosmos-2251, which was no longer operable, collided with the active Iridium 33 satellite in LEO, destroying both satellites and producing over 3,000 pieces of fragmented debris (NASA 2009a). Analysis suggests that the orbits that would most benefit from cleanup are on the 71–74 degrees inclination, 81–83 degrees inclination, or sun-synchronous clusters (Levin and Carroll 2012).

A number of methods have been proposed to remove debris from crowded orbits. Proposed methods to actively remove debris include using space tugs to move satellites that are no longer operating to safe graveyard orbits or thrusting a satellite to successfully de-orbit it. Ideas to thrust pieces of orbiting debris have included using a laser "broom" or laser beam photons whereby lasers are used to nudge debris to different orbits. Others have proposed collecting debris using foamy balls of aerogel, water spray, inflatable balloons, or boom electro-adhesion. Tethers Unlimited is developing Terminator Tape and Terminator Tethers that increase drag on a satellite or very large pieces of debris, resulting in de-orbiting. The company is also developing a net called GRASP (Grapple, Retrieve, and Secure Payload) to capture space debris (Tethers Unlimited 2015). The Aerospace Corporation is developing an extremely thin spacecraft that could wrap itself around debris and safely remove it from orbit (Johnson 2016).

For debris remediation in LEO, the RSV will require large amounts of propellant to travel between pieces of debris, especially if the RSV is propulsively moving the debris to lower orbits. Every encounter with a debris object will require a consumable, such as a net, tether, foam, etc. The decision to cache propellant and other consumables on an outpost versus sending them just-in-time on a d-OTV is more complex than the case for life extension services in GEO. The orbit of the outpost in LEO would be relatively static, but the RSV for debris remediation must traverse a wide range of possibilities in terms of both altitude and inclination. It may not be advantageous to burn propellant to return to the static outpost orbit compared to sending the necessary supplies to the location the RSV will be in when it runs low. For debris remediation in GEO, the situation is effectively the same as for life extension services; the main difference being that in this case the RSV will tug satellites to a graveyard orbit as part of the satellite's post-mission disposal plan.

Thinking further ahead, defunct satellites would be valuable if their subsystems or constituent materials could be recycled. An orbital outpost could also serve as a collection and storage site for debris. If recycling technology advances far enough, the outpost could be used as a recycling center. Using an orbital outpost in LEO as a port for orbital debris cleanup would be most effective if it existed near the most favorable orbital altitudes and inclinations to minimize fuel expenditures during inclination changes. We do not think this application is likely to materialize in the next decade or two.

4. Space Domain Awareness

Space domain awareness (SDA), also known as space situational awareness (SSA), is the surveillance and potential reconnaissance of objects in space. For this potential activity, we simply observe that if an outpost is operating in space, there is the potential to put an observational asset onboard to conduct space-based SDA. This may be appropriate for any of the outpost scenarios we have described. This activity alone may not provide sufficient revenue to the outpost, but it could serve as one among many lines of business for the outpost.

An outpost might also support space-based reconnaissance by hosting an RSV. The RSV may travel to visually inspect a target satellite, returning to the outpost to replenish consumables. This would not involve docking with the target satellite. Used in this way, an outpost would be providing a home base for the RSV; we chose to mention this activity here simply to reinforce its relation to SDA.

5. Orbital Space Range

Interviewees indicated that an outpost might be used to train members of the U.S. Space Force (USSF) on TTPs for the space domain. We effectively addressed operational testing of space systems in our discussion of adverse events testing, but we did not consider the possibility that the tests would be conducted as part of a training exercise. For instance, rather than testing new technologies for use in RPO, the test may involve a human operator performing aspects of RPO that cannot be automated.

We are unable to assess the potential for this activity to be hosted on an outpost and only offer the following considerations. The Chief of Space Operations for the USSF, General John Raymond, released official guidance related to the "capabilities and culture the USSF will pursue over my tenure" (Raymond 2020). In the document, he states, "We will make every effort to train in realistic, contested conditions." This could be interpreted as support for training on physical hardware in space, such as an outpost. However, in the context of training in realistic conditions, he also states that the USSF "will develop and acquire in hi-fidelity simulators, virtual and augmented reality, and artificial intelligence to improve warfighting proficiency against a thinking, reacting adversary.” There is no mention of training on physical hardware in space. In this manner, he makes it clear that an orbital space range is likely to be virtual.

We view operational testing of hardware as important and valuable. Such testing can only be performed in an operational environment, because the purpose is to find fault modes or unanticipated design flaws that cannot be found in simulation. On the other hand, we are unable to identify a training opportunity in space that cannot be simulated adequately in software. Training exercises for the other military services may involve people literally moving and interacting with large pieces of physical hardware (e.g., boats, airplanes, and guns) that they have acquired due to their necessity in battle. In contrast, space operations are mostly controlled via computer and the outpost is not clearly a battle necessity—that must be acquired for reasons other than training. We find the use of an outpost as part of a personnel training program to be unlikely.

4. Conclusions and Recommendations

A. Viability of Outposts

The most promising application for an outpost is to perform technology refresh of large satellites. This use case is somewhat future-proof to the effect of large reductions in the cost of launch. Specifically, if launch costs go to zero, some satellites still represent a substantial investment in hardware that would justify the cost of a repair or upgrade. In this case, a single-tenant model appears more attractive than a multi-tenant model. A challenge with realizing the benefits of this use case are that it may be difficult to "start small," because smaller platforms may not justify the cost of performing an upgrade or repair.

The best use of a small outpost, using a multi-tenant model, is likely for application testing, where an expensive or massive piece of hardware is aboard the outpost that many different users would like to utilize. We examined the situation where the robotic arm on the outpost is itself the subject of experimentation and found that robotic arm experiments in space have the potential to be affordable by SBIR grants and small R&D projects at government labs. This likely requires the government to be an anchor customer to coordinate a portfolio of R&D funding around the capabilities installed on the outposts. For instance, if an additive manufacturing capability were installed on the outpost, government agencies would need to plan annual grant opportunities that seek to print and test articles in space using the capabilities of the manufacturing facility.

Other potential use cases for an outpost will face stiff competition from other platforms. This is the case for testing subsystems in space and microgravity R&D. Revenues may be possible, but the majority of customers for these services may be better served by other platforms. As a destination that simply provides power, communications, pointing, and thermal management, an outpost tends to be a more costly and risky[32] venture than using a short-lived, disposable platform that also provides those capabilities.

The main value of developing outpost technology is the maturation of modularity and SpaaS capabilities. In a future where those capabilities are mature, space platforms without

[32] A low-cost outpost is occasionally cheaper than a low-cost disposable platform, but high-cost outposts are generally far more expensive than high-cost disposable platforms. Outposts are also operationally more complex, requiring advanced robotic capabilities in space, multiple in-space transfers of payloads among various platforms, and a potentially complex scheduling problem among many simultaneous users of the outpost with diverse operational requirements. There are also numerous payload constraints that can make certain combinations of payloads, outpost scenarios, orbits, and other technical characteristics incompatible. For example, a manufacturing payload that generates vibrations could not operate on the same platform as a delicate microgravity experiment.

robotic arms and RPO capabilities generally outcompete platforms that include these costly additions. Regardless, modularity and SpaaS capabilities have the potential to reduce the cost and complexity of space access from the user's perspective, benefiting the entire space enterprise.

B. Drivers of Demand

The first orbital outposts may become operational approximately 5–10 years from now. As such, the potential costs and benefits of outposts, including our assessment in this report, are speculative. Many factors could influence demand for such a platform over the next few decades. In this section, we discuss some broad trends that may shape the entire space ecosystem, but which are not specific to orbital outposts and for which targeted government interventions to encourage outposts are unlikely. These trends are somewhat like forces of nature to which outpost providers must simply respond. In the subsequent section, we provide recommendations for how the U.S. Government could encourage the viability of orbital outposts.

1. Ultra-low Cost of Launch and Return

Decreasing costs of launching mass to orbit will have a mixed effect on the viability of orbital outposts. On the one hand, lower costs may bring more users into space, who may potentially become customers for an outpost. High launch costs hinder satellite modularity, because modularity increases the mass—and thus cost—of the space system; low launch costs reduce the costs associated with this mass penalty and may encourage satellite modularity. In these ways, lower launch costs may support the market for an orbital outpost.

We find the most valuable use for an outpost is to perform technology refresh. Even if launch costs went to zero, the value of the satellite hardware and the critical mission it serves may still warrant using an outpost. However, lower launch costs would allow for the development of more robust (i.e., massive) instruments, which would reduce the probability of failure and reduce the need for repairs. Likewise, reduced launch costs reduce the pressure to design costly or long-lived space systems; as the cost of the space hardware drops, the marginal benefit of performing technology refresh decreases compared to simply flying a new low-cost satellite.

While we have not explicitly analyzed it in this report, the SpaceX Starship may provide low-cost launch *and* return of large-volume payloads. A platform that provides low-cost return mass would likely outcompete an outpost for most markets that require return mass, such as in-space manufacturing for terrestrial customers or many types of microgravity R&D. Interestingly, if the cost of launch and return were low enough, it may also undermine the value proposition of an orbital outpost for technology refresh *in space.* As a thought experiment, a platform like Starship might be able to capture a defunct satellite, return it to Earth for repairs, and then launch the refurbished satellite back into orbit. This is not unprecedented. In 1984, the space shuttle captured the Westar 6 satellite and returned it to Earth. The satellite was refurbished and sold to AsiaSat, who launched it back to space in 1990 as AsiaSat 1.

2. Proliferated Constellations

As the industry moves toward disaggregation of large and monolithic space systems, there may be less need for an orbital outpost. For instance, the primary reason that technology refresh is a valuable use case for an outpost is that the cost of the hardware in space is sufficiently expensive to justify upgrades or repairs. If something like a GOES mission could be disaggregated into a constellation of smaller satellites, there would be less incentive to repair any individual failed satellite. Likewise, proliferated satellite systems offer greater redundancy and reduced risk of single-point failures, reducing the need to fix or replace a broken satellite immediately.

While the move to proliferated constellations may reduce demand for an outpost, there is a possibility that an outpost *reduces the incentive* for satellite owners to pursue proliferated systems. Two of the high-level benefits of proliferated systems and an outpost for technology refresh are the same: being more robust to failures and a reduced cost for payloads and platforms, enabled by designing systems that can fail without jeopardizing the mission. To the extent than an outpost is able to offer these benefits at a competitive cost, there may not be a need for proliferation in some cases.

3. Rules Concerning Orbital Debris and Space Traffic Management

Concerns regarding the damaging effects of orbital debris and efforts to establish a system for space traffic management may provide incentives that support the use of an outpost. In many of our comparisons, a d-OTV appears to outcompete an orbital outpost. However, future orbital debris regulations may make it more costly for a d-OTV to loiter in space while hosting payloads. For example, the FCC recently proposed a regulation that would require a satellite operator to post a bond payment, prior to launch, that would be refunded after the satellite successfully performs its post-mission disposal. If such a regulation passes, a d-OTV operator might be incentivized to de-orbit their vehicle as soon as possible, instead of staying in space while their assets are tied up in bond. Likewise, regulations regarding orbital debris may provide incentives against operating free-flying CubeSats, such as the FCC's proposed rule requiring "maneuver capability" on all satellites above a certain altitude. Payloads that currently would be flown on smallsats could be hosted together on an outpost, which would make de-orbiting all of the payloads relatively easy and likely faster than as free-fliers. If there are strong financial incentives to remove space vehicles from orbit as soon as their mission has ended, there would be fewer d-OTVs in space overall. These factors would reduce the cost and utility of a d-OTV compared to the use of an outpost.

Unlike the other drivers of demand, rules that aim to reduce the volume of orbital debris or traffic of small satellites do not appear to have a negative effect on the viability of outposts. The only caveat is that these same regulations would incentivize outpost providers to responsibly dispose of payloads after their missions have ended. Simply detaching the payloads and letting them float away would not be a viable approach. The space vehicles that bring the payloads to the outpost would also have to carry defunct payloads away.

4. Future Crewed Platforms

A crewed orbital platform may be able to attract most of the same revenue opportunities as a robotic outpost, along with other sources such as government astronauts and space tourists. Space tourists have already visited the Russian modules; space tourists are set to visit the U.S. modules later in 2021. The revenues associated with space tourists may run about $15–$20 million per customer for a few days of microgravity.[33] Government astronauts, both U.S. and foreign, may garner higher revenues and provide a stable base of revenue.

A previous analysis by Crane et al. (2017) showed that a privately owned and operated space station is unlikely to cover costs in most scenarios without substantial subsidies. However, NASA is currently supporting the development of crewed platforms to replace the ISS as part of its Commercial LEO Destinations (CLD) program. Subsidies for the development and operations of a crewed platform could make it solvent. In this case, NASA may continue to offer a heavily subsidized platform after the ISS is decommissioned, which will directly compete for many of the same customers as a robotic outpost. To improve the survival prospects for a robotically tended outpost, it could be integrated into the CLD program.

A commercially owned station could be an orbital research park consisting of a crewed platform and an uncrewed platform that co-orbit each other when they are not docked together. This would allow each platform to specialize in those activities for which it is best suited, potentially reducing costs and increasing customer appeal. For instance, when hosting tourists, the crewed module could detach from the robotic module, allowing R&D experiments to function undisturbed while tourists bounce around the cabin. When government astronauts visit the research park, the crewed and robotic platforms could dock, so that experiments or production equipment can be tended; this would reduce the requirements for automation of experiments, production facilities, and payload handling

[33] Ticket prices may be about $55 million per person. The total cost of crew dragon launch is about $150 million for a crew of 4—about $37.5 million per person.

inside pressurized volumes. Periodic interactions with a crew provide a valuable opportunity to repair any equipment that has malfunctioned or failed on the robotic platform. Finally, the robotic platform may detach in order to perform functions that might otherwise be too dangerous for a crewed platform. Depending on costs and demand, there could be multiple robotic platforms in the research park that can interact with the crewed platform. Financial support for the crewed portion of the platform would defray some of the costs of the co-orbiting robotic platform.

Alternatively, another option is to have a single crewed platform that is tended intermittently by humans. Typical discussions of crewed versus uncrewed platforms seem to implicitly assume that a crewed platform always has crew aboard. For instance, an advertised benefit of a robotic outpost is that it could perform functions that are too dangerous or costly to perform in the presence of crew. An intermittently crewed platform could have smaller development and operations costs than a permanently crewed platform and be able to use the uncrewed portions of its flight to host experiments that are incompatible with human safety issues. One element of U.S. National Space Policy states that the U.S. shall "maintain continuous human presence in Earth orbit by transitioning from ISS to commercial platforms and services" (U.S. White House 2020). A somewhat creative interpretation of this policy would allow for an intermittently crewed platform—specifically, if the times when the station in LEO is uncrewed overlapped with the times when Artemis astronauts are performing lunar missions.[34] In this scenario, it would be more challenging for a robotic platform to take advantage of the subsidies for a crewed platform, which would be a direct competitor for a robotic outpost.

5. U.S. Presence on Lunar Surface

To first order, we do not see a U.S. presence on the lunar surface as affecting demand substantially for an outpost. However, lunar orbital elements may one day be candidates for technology refresh or application demonstration. In Earth orbit, we found limited utility for technology refresh of small satellites; however, the cost per kilogram of delivering mass to lunar orbit may be sufficiently great to justify using an outpost. If materials can be mined from the lunar surface and delivered to an orbital outpost efficiently, an outpost might support experiments regarding the use lunar materials to manufacture novel structures. For instance, the Defense Advanced Research Projects Agency (DARPA) has recently announced the Novel Orbital and Moon Manufacturing, Materials and Mass-efficient Design (NOM4D) program. NOM4D's focus appears to be mainly on using Earth materials to manufacture "incredibly precise and mass efficient" structures in space, but the program "will also explore the unique features of in-situ resources obtained from the Moon's surface

[34] The quoted U.S. policy only calls out "Earth orbit" and clearly the Moon orbits the Earth.

as they apply to future defense mission" (DARPA 2021). This program or a successor effort may eventually support tests and demonstrations that support or leverage lunar activities.

The same technologies required for an orbital outpost might be extensible to the lunar surface. For instance, a lunar rover could be designed with the same philosophy as an orbital outpost. Rover subsystems could be modularized and capable of hot swapping. This approach would provide mission-enabling capabilities. Specifically, a rover could more easily survive the lunar night if its batteries were charged at a separate power station and inserted into the rover as necessary. The power station could charge multiple batteries at once, storing enough power for the rover to not only survive the lunar night, but to carry on with its nominal operations. A rover that does not charge its own batteries does not need to carry fragile solar panels, making it more robust and lighter mass. There are many challenges unique to the lunar environment, such as the omnipresence of dust and a challenging thermal environment, but an outpost provider that has mastered satellite modularity and on-orbit servicing may have an advantage when it comes to designing lunar surface elements.

C. Recommendations

DoD investments should likely not focus directly on the development of an outpost, but rather on the development of the supporting services required: SpaaS, satellite modularity, and satellite servicing. As these technologies mature and the utility of their use cases are proven (or disproven), their economic viability will become clear. Once these capabilities are mature, government or private providers can determine whether a stand-alone outpost is valuable to pursue or whether the existing SpaaS, modularity, and servicing capabilities are sufficient. We see the creation of an orbital outpost as happening organically and without further government support, once these three supporting capabilities are developed.

1. Use Acquisition and Development Contracts to Support Satellite Modularity

The most valuable capability appears to be satellite modularity. This capability is likely to reduce the cost of space access whether payloads are integrated in space or on the ground. Modularity of payloads allows for the creation of a standardized set of interfaces that each payload owner can integrate their payload into and then "go shopping" for a SpaaS provider. Without such standardized interfaces and modularity, it will be difficult to develop a broad market for SpaaS. As previously discussed, modularity is also a mission-enabler for lunar surface operations. Modularity of payloads and satellite subsystems also allows for reduced integration costs; the MMS program realized a 50–90 percent reduction in integration and testing costs, which was sufficient to pay back the development costs after production of only a few MMS units (Dino et al. 2015). We cannot confidently state that modularity will reduce the overall costs of the satellite, but we find it plausible. Some authors have previously estimated that modularity adds 20 percent to the cost of a satellite (Long et al. 2007); however, that appears to be an assumption and not the result of analysis. Other than development costs, which will be recouped after a few flight units are produced, the other major cost element is likely launch costs. Modular systems are not optimized to reduce mass and thus will entail a mass penalty. However, as launch costs fall, the cost associated with such a mass penalty falls as well. On balance, the benefits of modularity appear to outweigh the costs for the future space ecosystem.

Both DoD and NASA are equally suited to supporting the development of this capability. The most fruitful method of support would be for both agencies to commit to using modular buses for a specified number of future missions. In the near term, the cost of the resulting missions may increase somewhat as satellite providers develop the requisite modularity capabilities. On the other hand, an acquisition pull may relieve the government of providing development contracts as companies spend their own internal R&D dollars to meet the demands of their customers; this approach may be overall the more cost-effective way to develop satellite modularity.

DoD and NASA could use development contracts to mature satellite modularity capabilities. This may be an acceptable interim solution while the agencies determine the scope of future acquisition contracts they can offer. Development contracts would also help to lower the cost of the resulting systems by covering some of the development costs. However, development contracts do not ensure that the resulting systems will ever get used. Only the promise of future customers will induce the successful development of this capability. For example, the Commercial Orbital Transportation Services (COTS) contract was successful, in part, because COTS providers knew that they would eventually be able to compete for the Commercial Resupply Services (CRS) contract.

2. Develop Standards with Industry, Academia, and International Partners

Satellite modularity and SpaaS capabilities may falter without an agreed-upon set of standardized interfaces for the industry to design around. The U.S. Government should convene foreign and domestic stakeholders from industry, academia, and government to develop the standards required for modularity of satellite subsystems and payloads. As these standards are likely to be technical, the National Institute of Standards and Technology (NIST) or the International Organization for Standardization (ISO) may be appropriate governmental and non-governmental organizations to lead the development effort. Formation of a market will be incentivized if a payload operator can build to a standardized interface and then shop among the various SpaaS providers that can easily integrate the standardized interface.

3. Cultivate a Network of SpaaS Providers and Single Point of Contact at Agencies

There will be a required paradigm shift on the part of the owners of payloads; by force of habit, they may continue to design full satellites around their payloads or insist on bespoke integration rather than taking a modular approach. DoD and NASA can encourage the use of SpaaS by identifying current and emerging SpaaS providers, then ensuring that programs developing space hardware are acquainted with the services of the SpaaS providers.

DoD already offers SpaaS through its Space Test Program (STP). STP provides a form of SpaaS for in-space testing of defense payloads, either by integrating and launching test payloads on a dedicated bus or integrating test payloads onto a payload adapter that can be hosted on the external portion of the ISS. The launch services used to fly the payloads are provided by DoD or NASA, respectively, making them effectively free to the payload owner. The test articles are developed and funded by the organization that owns them, not STP.

An initial step to encourage the use of SpaaS may be to increase the resources available to STP and to broaden its mission to include supporting the development of emerging SpaaS capabilities. The current annual budget of STP is $25 million, down from about $50 million before sequestration. Within its current annual budget, STP can fly about 10 test articles per year, selecting from a queue of 60 to 70 test articles, most of which are CubeSats. As discussed earlier, payloads small enough to fit on a CubeSat are unlikely candidates for an outpost; however, payloads that would benefit from SpaaS on a d-OTV could receive first priority, then STP could use CubeSats to fill the remaining d-OTV payload capacity if necessary. If a commercial method of SpaaS could rival or beat STP's current costs, then STP would have an incentive to spend its funds on the commercial method as a customer. To the extent that DoD makes STP the focal point for facilitating payload flights, it will be easier to transition from government to commercial services when the latter mature. STP can more easily interact with the network of SpaaS providers and contract for their services on behalf of the programs STP supports.

The ISSNL partnerships with hardware providers can also provide a helpful model to consider. The ISSNL has, over the years, invested in a network of "Implementation Partners," or flight hardware providers. Implementation Partners provide end-users with hardware tailored to the needs of their specific experiment as a paid service, whether the end-user pays directly or through ISSNL grants. Rather than creating such hardware "in house," investing in a network of providers offers two benefits. First, the Implementation Partners can use the hardware and expertise they have developed to then seek more customers and generate more demand for their services, and indirectly, for the ISS. Second, a strong ecosystem of providers is helpful in ensuring competitive pricing and a more sustainable market.

4. Proactively Engage on Orbital Debris Guidelines and Regulations

As discussed previously, future rules concerning orbital debris and space traffic management are drivers of demand. While DoD and NASA cannot control or predict these rules, these agencies can influence them. Frequent and forward-looking conversations with U.S. regulating agencies will be important. Rules of immediate interest are the FCC's regulation of orbital debris for commercial satellites and the U.S. Government's Orbital Debris Mitigation Standard Practices (ODMSP) for government satellites. The development of these rules appears to be more geared toward reducing the amount of orbital debris and does not fully consider the role these regulations may play in supporting the emergence of future space-based markets.

DoD and NASA could take two approaches. One approach is to encourage new rules that support emerging businesses activities that may benefit from using outposts. For instance, vehicles that perform active debris removal may wish to use an outpost as a home base, to cache propellant or other consumables. Current FCC regulations do not allow active debris removal as a viable method for post-mission disposal of a satellite, though such a regulatory change would encourage the formation of a market for satellite servicing and debris removal.

The other approach is to identify and alter regulations that may preclude the operation of an outpost. For instance, U.S. regulations regarding non-Earth imaging are rather restrictive, due to concerns regarding potential identification of U.S. intelligence assets. However, in-space imaging of satellites will be a key function needed for outpost operations. DoD should update such rules and regulations to allow greater flexibility for servicing missions while preserving security.

5. Coordinate Satellite Servicing Development with Outpost Development

As mentioned previously, if outposts provide value, they will likely evolve organically once SpaaS, modularity, and satellite-servicing capabilities are mature. While SpaaS and satellite modularity are likely to save customers money in the end, the costs of satellite servicing may be sufficiently high that few customers can afford to use the service. Indeed, the scenarios we analyzed that used high-cost robotic arms and high-cost RPO capabilities were not competitive with alternatives. DoD and NASA should consider ways to reduce the costs of satellite servicing that also support the emergence of an outpost.

For instance, DoD and NASA could coordinate the development of a research portfolio that advances satellite-servicing capabilities and that could only be performed on a persistent platform in space. The persistent platform does not need to be an outpost (i.e., satellite modularity and SpaaS are not necessary), but it would have to be capable of onboarding certain types of experiments. Specifically, a portfolio of SBIR awards for commercial partners and internal R&D projects for government labs could be sufficient to support a small platform that focuses on in-space robotic manipulation and additive manufacturing capabilities. The platform itself need not be developed commercially, so long as its operation demonstrates a potential market for in-space testing of such services. There may be opportunities to use platforms that are already nearly developed. For instance, after NASA's OSAM-1 mission is completed, the platform may be able to host subsequent experiments delivered to it. Once the platform ends its mission and the market for this service is clarified—perhaps after 5 years—a commercially developed successor could take the place of the previous platform.

6. Consider Requirements for In-Space Testing

Without a requirement for subsystem, operational, or adverse events testing in space, an outpost is unlikely to see broad adoption for these purposes. It is beyond our scope to assess which missions may benefit from in-space testing, which can be tested satisfactorily on the ground, and which could better address its vulnerabilities through proliferation. DoD should commission an independent assessment to identify missions that are vulnerable due to a lack of in-space testing and further identify the specific types of in-space testing capabilities that would be needed to address the vulnerability. If missions exist that are both vulnerable and can be reasonably addressed, then DoD could proceed to develop a requirement that space systems acquired for those missions be tested in space. With a requirement approved by the Joint Requirement Oversight Council (JROC), programs of record can request funds to perform the tests.

7. Communicating with the International Community

Considering DoD's support of persistent orbital platforms, the U.S. Government should make a coordinated effort to engage with the international community about their use. Outposts might be useful platforms for cooperative activities with our existing space allies and for developing new partnerships with countries that have emerging space capabilities. The international community is concerned with the potential weaponization of space. While the plans for the orbital platform are not to conduct weapons testing in space, such a perception could be a diplomatic hurdle. Early conversations within the international community on the intentions and boundaries of this program would go a long way in preserving an international collaborative framework in space. DARPA's Phoenix program, later the RSGS program, could serve as a model for such an effort. DARPA engaged with the broader space community for a number of years in anticipation of their on-orbit servicing mission, in anticipation of concerns over the possible dual use of such technologies.

Appendix A.
Current and Emerging Space Capabilities

In this appendix, we summarize the various supporting capabilities that outposts and their alternatives will require. These include less costly access to space, in-space transportation capable of performing RPO, and robotic arms. Without these capabilities, customers will be unable to deliver their payloads to the outpost.

Launch Vehicles

Anything that goes to space—whether an outpost, a payload on its way to an outpost, or an alternative to an outpost—will require a launch vehicle. For this analysis, we consider the use of the following vehicles. The costs calculated in this section are for total mass to orbit and do not consider the mass of possible cargo vehicles, which we calculate in a subsequent section.

SpaceX's Falcon 9 can be used to launch primary customers, secondary customers as rideshares, or to launch cargo in a Dragon capsule. A reusable Falcon 9 can deliver up to 15,600 kg of mass to LEO for a price of about \$50 million. For this analysis, we use \$3,200 per kg[35] as the cost charged for primary customers of a Falcon 9. For customers that wish to rideshare on a Falcon 9, the SpaceX cost calculator [36] estimates that a launch to LEO, Sun-synchronous orbit (SSO), or polar orbit costs \$5,000 per kg for masses between 200–830 kg. Systems with masses below 200 kg are charged a flat fee of \$1 million.

For launches to Geosynchronous Transfer Orbit (GTO), a reusable Falcon 9 can deliver approximately 3,500 kg to this orbit and return to the launch site. This leads to an approximate price of \$15,000 per kg, rounding up. SpaceX can deliver more mass (5,500 kg) if the Falcon 9 lands on a barge; however, we do not know the costs associated with the use of the barge and thus err on the side of using the nominally more expensive launch option. After being dropped off in GTO, a satellite or other in-space transportation vehicle must still burn at least 1.5 km/s of ΔV to reach a geosynchronous orbit—even more if the satellite requires a plane change.

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[35] \$50 million divided by 15,600 kg

[36] SpaceX cost calculator: https://rideshare.spacex.com/search

SpaceX appears to have the capability to place satellites directly into GEO with Falcon Heavy, evidenced by their recently awarded contracts to launch the USSF-44 mission. For this mission, SpaceX will deliver multiple payloads with a combined mass up to 3,700 kg (Clark 2021). The mission will be partially reusable, with both side boosters returned to Earth; however, there will not be sufficient remaining propellant to recover the core stage. For the purposes of analysis, we use the fully expendable price of $150 million. Thus, we estimate the cost of launching directly to GEO on Falcon Heavy is approximately $40,000 per kg.

ULA's Vulcan is expected to fly in July 2021, delivering the Astrobotic Peregrine lander to the lunar surface. More importantly for our analysis, Vulcan is the launch vehicle of choice for the Dream Chaser spaceplane, which is a potential competitor for an outpost. ULA (2019) estimates that Vulcan will be capable of delivering 10,000 to 27,000 kg of mass to LEO, depending on the configuration, with a target cost of $100 million (Clark 2015). We assign Vulcan a cost of at least $2,700 per kg.[37]

Rocket Lab's Electron is reported to cost about $5.7 million; however, an Electron more often costs about $7.5 million (Davenport 2020) so we use this price for our launch cost estimates. It is capable of delivering 200 kg to 500 kilometer to SSO and 300 kg to lower orbits in LEO (Rocket Lab n.d.). That translates to a cost of about $25,000 per kg to LEO[38] and $37,000 per kg to low SSO.[39]

Relativity Space's Terran 1 is advertised as delivering 1,250 kg to LEO (185 km), 900 kg to low SSO (500 km), and 700 kg to high SSO (1200 km) (RelativitySpace n.d.). The cost of a mission is advertised at about $12 million.

Spaceflight Sherpa. Spaceflight openly advertises their pricing information. Launching CubeSats to LEO costs $50,000 per U up to 12U. Launching CubeSats to GTO costs about $230,000 per U (Spaceflight 2021).

For the purposes of our analysis, we exclusively use the prices based on the SpaceX vehicles. This is not because we believe that SpaceX vehicles will be used in the future, but rather because using a consistent set of prices for all scenarios will allow for an apples-to-apples comparison between scenarios. We have provided launch costs associated with a variety of launch vehicles to contextualize the SpaceX costs. We do not provide cost estimates for many important launch vehicles (e.g., Antares) because those costs are not needed for this analysis.

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[37] $100 million divided by 27,000 kg. This is likely an optimistic estimate. A more conservative estimate would divide by 10,000 kilograms to find $10,000 per kilogram.

[38] $7.5 million divided by 300 kg.

[39] $7.5 million divided by 200 kg.

Table A-1. Comparative Costs of Launch Vehicles

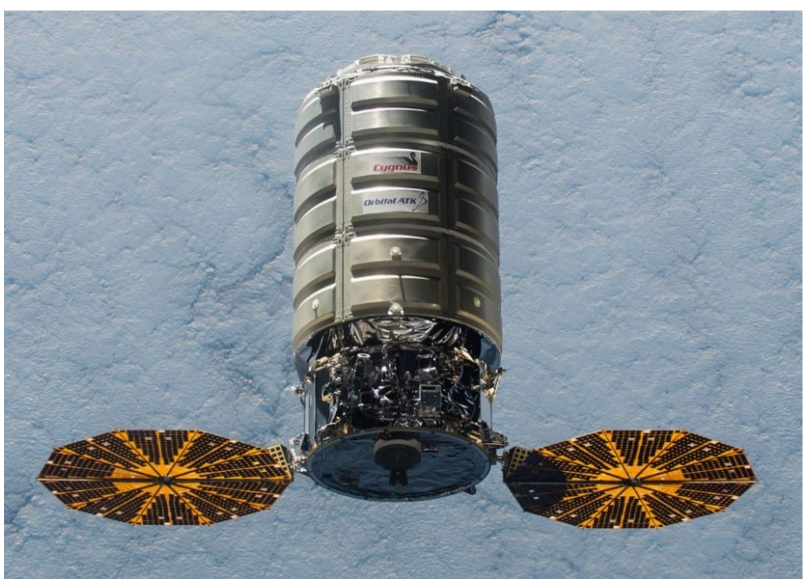
System	Service	Destination	Cost per Kilogram
Falcon 9	Primary Launch	LEO	$3,200
	Rideshare	LEO, SSO, Polar	$5,000
	Primary Launch	GTO	$15,000
Falcon Heavy	Primary Launch	GEO	$40,000
Vulcan	Primary Launch	LEO	>$2,700
Electron	Primary Launch	LEO	$25,000
		SSO (500km)	$37,000
Terran 1	Primary Launch	LEO	$10,000
		SSO (500km)	$13,000
		SSO (1200km)	$17,000

System	Service	Destination	Cost per U
Sherpa	CubeSat Launch	LEO/SSO	$50,000

Source: Clark 2015, Rocket Lab n.d., Davenport 2020, Relativity Space n.d., STPI Calculations

Cargo Vehicles

Disposable Capsules



Credit: NASA

Figure A-1. Northrop Grumman's Cygnus Capsule

The Cygnus spacecraft is a disposable cargo capsule owned by Northrop Grumman that regularly provides transportation services to the ISS as part of the CRS contract with NASA. Cygnus has two design variants, standard and enhanced. Representative technical specifications for each variant are shown in Table A-2. For the purposes of our analysis, we use the specifications associated with the Enhanced Cygnus.

Table A-2. Technical Specifications of the Cygnus Cargo Capsule and Service Module

Specification	Standard Cygnus	Enhanced Cygnus
Length (m)	5.7	6.9
Diameter (m)	3.1	3.1
Up mass (kg)	2,000	2,700
Pressurized volume (m3)	18.8	27
Flight Duration	1 week to 2 years	1 week to 2 years
Power (kW, peak)	3.5	3.5
Wet Mass	-	4,600

Source: All numbers reproduced from FAA 2013

We estimate the cost of a Cygnus capsule using the value of the CRS-1 contract with Orbital ATK is $2,891 million.[40] Under this contract, 11 missions were flown to deliver Cygnus capsules to the ISS, leading to a cost of about $260 million per mission. The Cygnus launches atop an Antares rocket, which has a cost of about $80 million per launch (GAO 2017). Thus, the cost of a Cygnus alone is approximately $160 million. This appears reasonable when compared with the $300 million development cost of the system (Clark 2013); $160 million is approximately half of the development cost—in line with our heuristic.

Reusable Capsules

The Dragon capsule is a reusable cargo capsule owned and operated by SpaceX that is capable of carrying pressurized and unpressurized cargo to destinations in space. We do not investigate the crew-rated variant of Dragon. The technical specifications for a cargo Dragon are given in Table A-3. The vehicle can take about 6,000 kg of payload up-mass; however, typical payloads delivered to the ISS are approximately 1000 kg, likely due to volumetric constraints. Cargo Dragon has an assumed orbital lifetime of up to 2 years if left on orbit or 5 reentries if brought back to Earth.

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[40] Contract #NNJ09GA02B

Table A-3. Technical Specifications for SpaceX Dragon

Element	Value
Unpressurized Up-Mass (kg)	3,300
Unpressurized Down-Mass (kg)[a]	2,600
Unpressurized Volume (m3)	14
Pressurized Up-Mass (kg)	3,300
Pressurized Down-Mass (kg)	3,000
Pressurized Volume (m3)	10
Flight Duration	1 week to 2 years
Power (kW) (avg \\ peak)	2 \\ 4
Wet Mass (kg)	5,800

Source: Based on SpaceX 2010 and 2011

[a.] Burns up on reentry

To estimate the mass of Cargo Dragon, we note that for a test of the abort system, the trunk and capsule are reported to contain 1,590 kg of propellant and other mass of 9,525 kg (Evans 2015). The article does not state what is contained in this mass. In context, we assume this is the dry mass plus payload mass. This is a reasonable assumption because the total stack mass on the test stand equals the payload capacity of a Falcon 9 v1.1, which was about 11,000 kg to LEO (SpaceX 2015). SpaceX reports that the cargo Dragon capsule and trunk has a dry mass of 4,200 kg (SpaceX 2012). Thus, the wet mass of the vehicle is approximately 5,800 kg.[41] Dragon trunk has average power of 1.5 to 2 kw and peak power of 4kw (dragonlab datasheet).

We very roughly estimate the cost of the Dragon capsule at $200 million per unit. This is reasonable from the perspective of its likely development costs. The total cost to develop Falcon 9 v1.0, cargo Dragon, and launch facilities at Cape Caneveral is estimated at approximately $1 billion (Shotwell 2014).[42] Previous estimates of the development cost for Falcon 9 are approximately $400 million. We roughly assume that development of the launch pad cost $200 million. We assume the remainder of the funds, $400 million, was spent on Dragon. A $200 million unit cost for Dragon is half of the development cost, which is reasonable. This cost is also reasonable from the perspective of the costs that SpaceX charges NASA. NASA pays about $100 million per use of a Dragon[43] and, since

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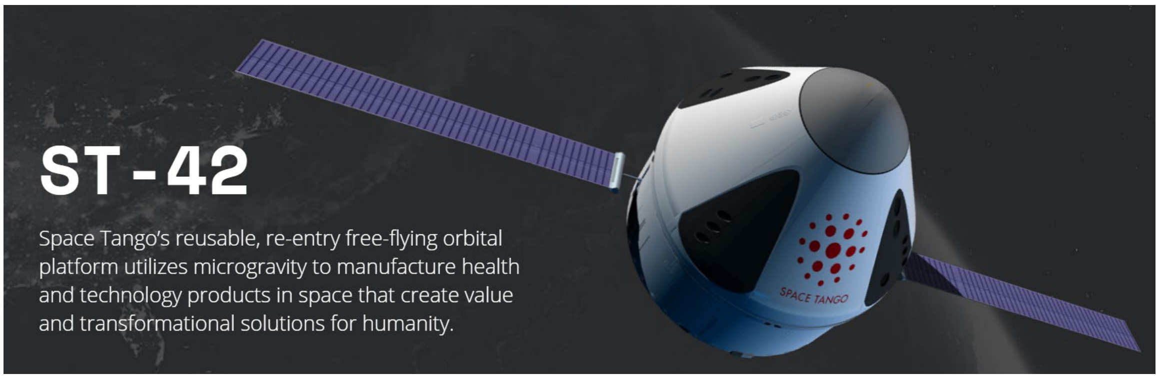
41 That is 4,200 kg of dry mass plus 1,590 kg of propellant.

42 Shotwell states that NASA provided $396 million while SpaceX provided over $450 million, for a total of $846 million. Assuming those are 2010 dollars, the cost in 2020 dollars would be $1 billion.

43 SpaceX's CRS-1 contract (#NNJ09GA04B) has approximately $3 billion in total obligations. Under this contract, they performed 20 deliveries to the ISS. This is a cost of $150 million per delivery. Subtracting the cost of a reusable Falcon 9 ($50 million), leaves approximately $100 million per use of the Dragon capsule.

the vehicle is reusable up to five times, SpaceX would recoup their cost after its first two uses.

Other companies, such as Space Tango, are also developing reusable cargo capsules. The internal volume and payload masses are much smaller, because the capsules are being designed specifically to service customers buying microgravity services. We do not have enough information to analyze the cost and performance of these capsules.



Source: Space Tango website

Figure A-2. Space Tango Plans a Free-flying, Capsule for Microgravity R&D and In-space Manufacturing

Spaceplanes

A spaceplane is a winged space vehicle that launches atop a rocket and returns from orbit by landing on a runway. Notable examples include the Space Shuttle, Dream Chaser, and the X37-b. Similar to cargo capsules, they can potentially provide pressurized volumes for payload delivery to orbit and return to Earth. Compared to capsules, space planes are attractive options for returning sensitive payloads. Landing gently on a runway reduces the forces applied to reentering payloads. Experiments can be retrieved immediately after landing. However, existing spaceplanes have less up-mass and down-mass capability than capsules. They also do not tend to have as much power available for the payloads.

The Sierra Nevada Dream Chaser is one example of a spaceplane. As a free-flier, the Dream Chaser also launches with an attached cargo module, as shown in Figure A-3. The cargo module contains the solar panels required for power to the system. The combined stack can carry up to 5,500 kg of mass to the ISS in LEO. The Dream Chaser can return about 1,750 kg to Earth (Saccani 2019). The cargo module is disposed of in space; it is not returned to Earth. The inside of the vehicle can accommodate about 35 middeck lockers (MDL) and provides 75W of power to each MDL, which implies that the vehicle is capable of about 2.6kW in total (Saccani 2019). The total pressurized volume of the Dream Chaser and the attached cargo module is approximately 15 cubic meters (Saccani 2017). We make the simplifying assumption to split the pressurized volume evenly between the Dream

Chaser and the cargo module, giving each a pressurized volume of about 7.5 cubic meters. However, we note that each MDL is approximately 0.057 cubic meters of internal pressurized volume, leading to a total useable/powered volume of about 2 cubic meters in total (Saccani 2019). If a single customer were to lease the entirety of the Dream Chaser for the customer's own use, the customer would not have to use MDLs; in which case, we roughly assume that the Dream Chaser could hold double the pressurized volume—up to 4 cubic meters.

Source: Saccani 2019

Figure A-3. Dream Chaser

We estimate that a Dream Chaser mission costs about $40 million not including launch costs. John Curry, CRS-2 program director at the company, stated in an interview that launch vehicle costs are about 80 percent of total mission costs (Foust 2018). At the time, the Dream Chaser was planned to fly on an Altas V, which has an approximate cost of $164 million (Clark 2015). Assuming that the other 20 percent of the mission cost is the Dream Chaser leads to a cost of about $40 million per use of the Dream Chaser and the cargo module.[44] This translates into a cost of about $5,500 per kg to use the Dream Chaser vehicle,[45] excluding the cost of Atlas V launch. The customer also has to pay the per-

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[44] If $164 million is 80 percent of the total mission cost, then the total mission must cost $205 million. This implies the Dream Chaser plus cargo module has a price of $41 million per flight.

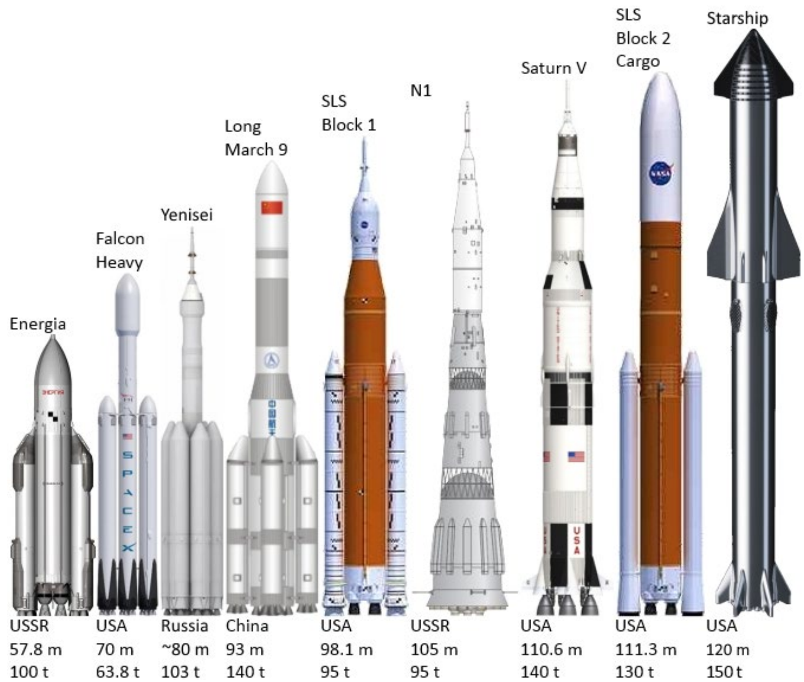
[45] Assuming that the full up-mass and down-mass capacity is used by paying customers—an optimistic assumption—leads to a total of 5,500 + 1,750 = 7,250 kg transported. Assuming that up-mass costs the same as down-mass, leads to a cost of $40 million/7,250 kg = $5,500 per kg.

kilogram costs associated with the launch vehicle, which will not necessarily be an Atlas V in the future.

The X-37B is a currently operational spaceplane that actively hosts defense-related payloads. There is not much publicly available information on the platform or its services. In 2010, the X-37B was reported to cost about $200 million per launch (Gresham 2011). With an Atlas V of approximately $164 million, as stated above, the cost per use of an X-37B itself may be approximately $40 million—roughly the same as the cost of Dream Chaser.

Starship

Another alternative to an orbital outpost is a new rocket being developed by SpaceX. The SpaceX system we analyzed is a heavy lift two-stage rocket currently under development. It is targeting a payload to LEO of at least 100 metric tons, with a desire to increase payload capacity to 150 metric tons in the future. The rocket is also being designed to have the capacity to send 100 people into LEO. The first stage of the rocket is called the Super Heavy. The upper stage is called Starship. The Starship is customizable depending on the mission; variants of Starship are designed to carry only cargo, carry only propellant, or be crew-rated. Figure A-4 shows the full Super Heavy plus Starship stack on the right compared to other historical and proposed heavy lift vehicles.



Source: Thorenn[46]

Figure A-4 Super Heavy and Starship Stack Compared to Other Heavy Launch Vehicles

We have developed a cost and performance model of the SpaceX Starship, the details of which are beyond the scope of this report.[47] Regarding performance, the model incorporates the masses (dry, propellant, and payload) of the first and second stages of Starship, the specific impulses of the Raptor engines under varying atmospheric pressures, the ΔV required for both stages to fly back to Earth, and the number of flights a single unit of the first or second stage may provide over its lifetime. In all cases, we assume that Starship will be capable of lifting 100 metric tons to LEO. Further, Starship arrives in LEO with enough propellant that it could return up to 100 metric tons of payload to the surface of Earth. The model also incorporates costs, including the development, unit, and operations costs associated with each stage. The model calculates the total cost of a single launch by amortizing all of the costs over 10 years and an assumed mission cadence.

We estimate that the cost of launching a Starship to LEO ranges from $50 million under optimistic assumptions to $200 million under pessimistic assumptions (Table A-4). We do not claim that these are lower or upper bounds; rather that they reflect a reasonable range of what might be expected. We surmise that the upper bound on cost is likely around $250 million; that would produce a cost per kg of $2,500, which is approximately the cost

46 Thorenn / CC BY-SA (https://creativecommons.org/licenses/by-sa/4.0). Image found at https://commons.wikimedia.org/wiki/File:Super_heavy-lift_launch_vehicles.png

47 Reports that detail the full model, including cost and performance assumptions, may be available upon request, contingent upon securing the proper permissions.

of launching on a Falcon Heavy. SpaceX has claimed that Starship will replace the Falcon line of vehicles, thus Starship should cost less than or equal to the best price achievable with a Falcon. The lower bound on cost will depend on the reuse rate of the vehicles. Under our optimistic assumptions, we assume that a single Super Heavy will be flown 20 times and a single Starship will be flown 10 times. Under our pessimistic case, a Super Heavy can fly 10 times and a Starship can fly 5 times. We acknowledge that the pessimistic case will still be seen by many in the industry as being optimistic; however, these reuse rates are close to the proven flight rates of the Falcon 9 first stage and the Dragon capsule.

Table A-4. Estimated Costs Associated with the Use of Starship

	High ($/kg)[a]	Low ($/kg)[b]
Starship Up-Mass[c]	$2,000	$500
Starship Down-Mass[d]	$2,000	$500

a. Calculated using the high mission cost of $200 million

b. Calculated using the low mission cost of $50 million

c. Cost is amortized evenly over up-mass of 100 metric tons and no down-mass

d. Cost is amortized evenly over up-mass of 50 metric tons and 50 metric tons

Satellites

Large Satellites

We use the SSL-1300 bus to model the cost and performance of large satellites. This bus is one of the most-used spacecraft in history, having launched over 100 times in the last 30 years. It is currently being used for NASA's OSAM-1 mission. We were unable to find specific information on the SSL-1300 bus being used for OSAM-1, so instead we rely on technical specifications listed for the same model of bus by the NASA Rapid Spacecraft Development Office (RSDO). The SSL-1300 has a dry mass of 916 kg, a chemical bi-propellant capacity of 2,272 kg (nominal) or 3,800 kg (maximum) (RSDO 2016). The bus is capable of delivering 4,073 meters per second of ΔV. The payload mass is 500 kg nominally, leading to a total spacecraft mass of approximately 5,300 kg. The bus can provide approximately 3 kW available to payloads.

We estimate the bus costs approximately $125 million. This is based on SSL's firm fixed price contract to NASA for design, fabrication, integration, testing, and delivery of the spacecraft bus for the OSAM-1 mission (formerly Restore-L).[48]

48 Contract #NNG17FB00C. The initial contract was worth $127 million in 2016.

Small Satellites

We use a Blue Canyon ESPA-class satellite as a model for small satellites. Specifically, we use their Saturn-class X-sat bus. This bus can provide nearly 800 Watts of power (Blue Canyon 2020). It has an orbital lifetime of more than 5 years in LEO and more than 2 years in GEO or deep space. According to the DACIS database, both DARPA's Blackjack Program and NASA's Phase III SBIR program have purchased this bus at a cost of about $5 million each.

CubeSats

We assume the cost to make a CubeSat, including the payload, is $50,000 per U (Kalman 2008)[49] and that the average CubeSat is 3U; the total cost of hardware is about $150,000. In a standard configuration, 1 U would be used to keep the satellite alive (power, communications, etc.), the next 1 U would be used for the Attitude Determination and Control System (ADACS), and the final 1 U being used for the payload. For systems that do not require ADACS, that 1 U of volume could be used for payload instead.

Robotic Arms

Outposts will require one or more robotic arms for transferring payloads from the in-space transportation vehicle to the outpost. The arm may permanently reside on the outpost itself or the arm could reside on a satellite-servicing vehicle that installs payloads on the outpost. Costs of robotic arms have tended to run in the tens of millions of dollars and often over $100 million (Wall 2019). One expert on robotic arms for space applications noted that the cost of an arm that can handle berthing is 2–3 times more expensive than an arm that does not perform berthing, all else being equal. However, for the purposes of our analysis, we will not make a distinction in cost between arms that are used for berthing and those that are not. Instead, we assume for simplicity that the robotic arm is capable of performing both functions.

We roughly estimate the costs of robotic arms using OSAM-1 as a reference point. For that mission, Maxar Technologies is producing three robotics arms, two of which appear to be used for servicing the Landsat 7 satellite, while the third is used solely for on-orbit assembly as part of the SPIDER experiment (NASA 2021). Based on renderings of the OSAM-1 spacecraft, we estimate that the other two arms are approximately the same size. The contract for the structural elements of the arms is approximately $150 million.[50]

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[49] This reference is a thread from the Pumpkin user forums. Note that the person posting with the handle "aek" is Andrew Kalman, co-founder of the company.

[50] DACIS database does not provide a contract number, but notes that "NASA Goddard Space Flight Center (GSFC) (Greenbelt, MD) awarded Maxar Technologies Holdings, Inc. (San Francisco, CA) a $142.0 million contract," in response to the Restore-L Robot Arm Composite Tube Assemblies Solicitation.

Interviewees indicated that incorporating costs of electronics and software might double the total cost to produce the arms, bringing the total to $300 million. Roughly assuming that each arm costs the same, the arms are worth about $100 million each, with most of this being development costs. In the future, when robotic arm technologies are mature, the unit costs may be less than this. We do not have a firm basis for estimating such cost reductions, so we simply reduce our estimate to about $60 million per arm. This is our high-cost estimate.

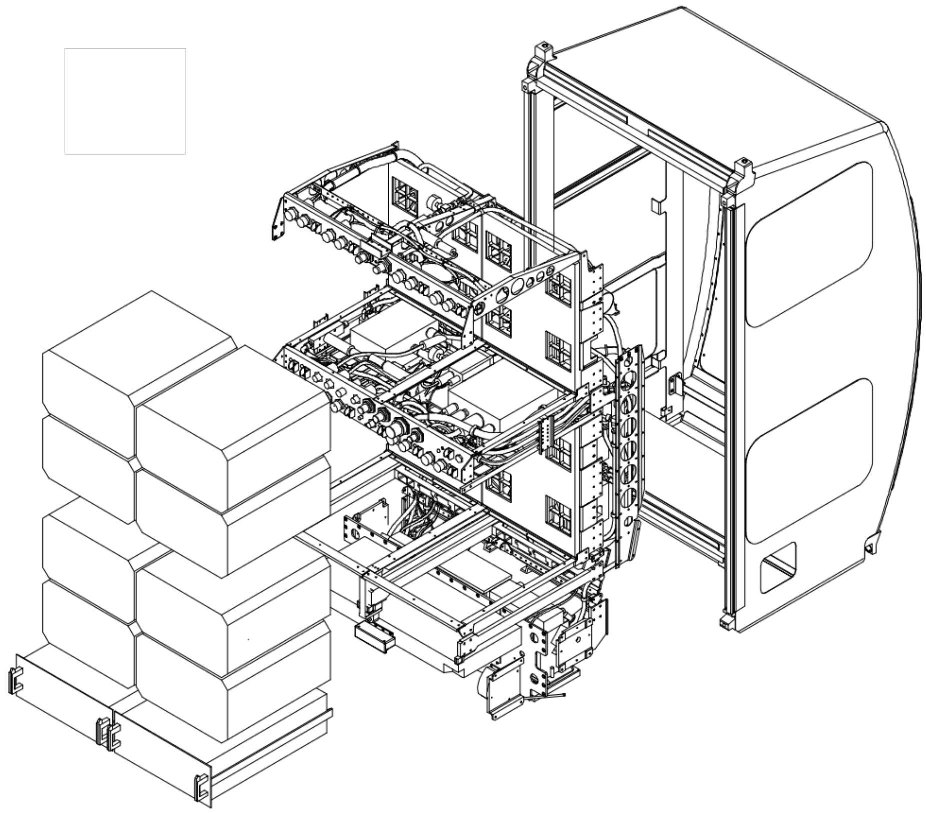
A recent paper by the former program manager of DARPA's Robotic Servicing of Geosynchronous Satellites (RSGS) program provides an alternative estimate. Roesler (2020) estimates that an 8 meter, walking robotic arm would cost approximately $15–$30 million. We use Roesler's estimate of $15 million per arm as our low-cost estimate.

Prior to OSAM-1, Maxar was working on similar robotic arms for the Dragonfly program. Maxar's design for Dragonfly was a 5-meter arm with 7 degrees of freedom. It had end-effectors at both ends of the arm, making it capable of "walking" around the spacecraft. Including its on-arm avionics, controls, and video processing capabilities, the entire arm had a design mass of 76 kg (Space Foundation 2019). For the purposes of our analysis, we will assume that all robot arms used in free space will have these capabilities and a flight mass of 75 kg. As a rough approximation, we assume that robot arms to be used within pressurized vehicles will have the same capabilities but, being smaller, will have only 50 kg of mass.

Microgravity R&D Equipment

Microgravity R&D experiments tend to require specialized equipment. Recognizing that there are many different classes of microgravity R&D experiments and that each may require their own specialized equipment, we instead provide only a very rough estimate of the masses and costs associated with such equipment. Instead of provided estimates that are specific to each scientific area, we assume that our generalized estimates are sufficient for illustrative and analytic purposes. We focus our estimates on the following pieces of equipment.

EXPRESS Racks



Credit: International Space Station User's Guide 2.0 (NASA n.d.d)

Figure A-5. ISPR, EXPRESS Rack, and Middeck Lockers for Hosting R&D on the ISS

Many experiments on the ISS are hosted inside of "middeck lockers." The left side of Figure A-5 shows eight of these lockers. Below these lockers in the figure are two other storage locations for hosting experiments, called ISIS Powered Racks. The lockers and powered racks are integrated into an EXPRESS[51] rack, shown in the middle of Figure A-5, which provides power, data, and other services to the experiments. In turn, the EXPRESS rack sits inside of an International Standard Payload Rack (ISPR), shown on the right side of the figure, which is attached to the hull of the ISS.

The ISPR has a mass of about 100 kg and takes up a volume of 1.6 cubic meters. It can accommodate an extra 700 kg of mass, which in this case is the total mass of the EXPRESS rack, 8 middeck lockers, and 2 ISIS Powered Racks, and the masses of the experiments contained therein. For the sake of calculation, we assume a single middeck locker has equivalent experiment capacity as two ISIS lockers. Thus, there are nine Middeck Locker Equivalent (MLE) slots per rack. We set aside 10 kg for experiments per

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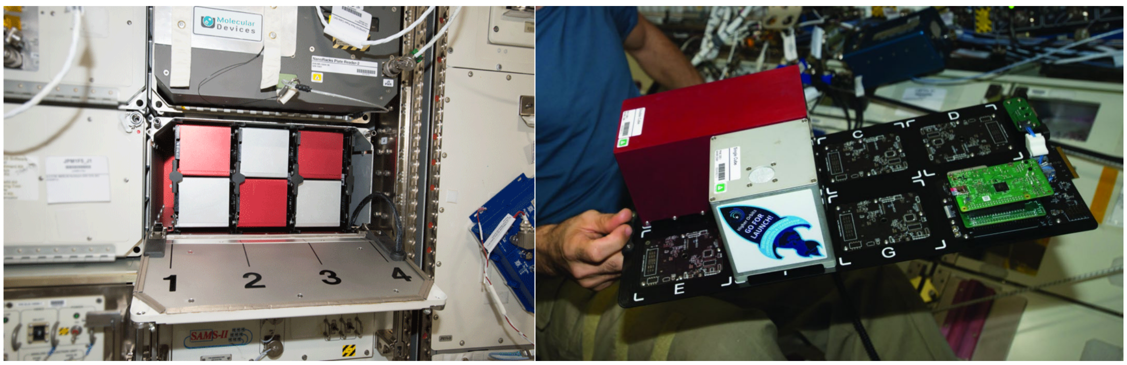
[51] EXPRESS stands for EXpedite the PRocessing of Experiments to Space Station

MLE, which leads to 90 kg of experiments. The remaining 610 kg is assumed to be the structural mass of the EXPRESS rack and lockers.

We have no basis for an estimate of the cost of the ISPR or EXPRESS Racks, but as they are not exposed to the space environment, we assume they are relatively inexpensive. We place the unit cost for an integrated ISPR and EXPRESS rack unit at $5 million each.

CubeLab Racks



Credit: Left: Space Tango 2018, Right: NASA n.d.b

Figure A-6. Pictures of the Space Tango CubeLab Indicate That One MLE Can Hold 24U of Experiments in 3 Racks of 8 Units

Multiple companies have developed the infrastructure to easily host microgravity experiments on the ISS using the same design principles that were popularized with CubeSats. Shown in Figure A-6 is that CubeLab solution designed by Space Tango, which we use as a reference system for this capability. Based on photos, it appears that a single middeck locker can hold 24 experiments, each the size of a 1 U CubeSat. For simplicity, we do not estimate the hardware mass or cost; instead, we assume that the mass and cost is sufficiently contained within the mass and cost of the EXPRESS racks that host the CubeLabs. Each U of payload on a CubeLab is allowed a maximum draw of 2 Watts (Kentucky Space 2011).

Pressurized CubeSats

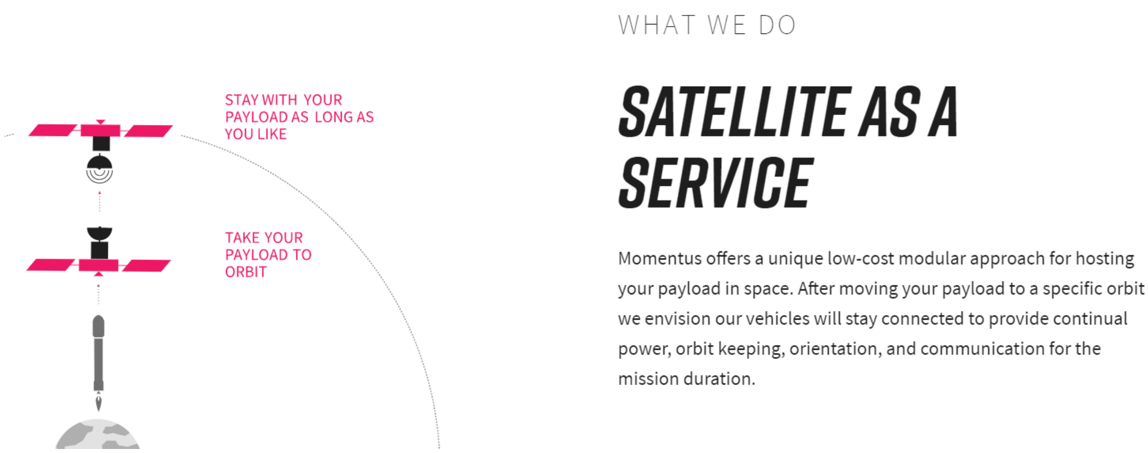
Pressurized microgravity R&D can be performed on CubeSats, as demonstrated by SpacePharma's DIDO satellites. DIDO 2 was launched in 2017 and DIDO 3 was launched in 2020 (Chemla 2020). Orbital Transports, Inc. has a similar design; however, we are unsure whether it has been manufactured or launched. We use the capabilities developed by SpacePharma as our point of reference for the cost and performance of a pressurized CubeSat for microgravity R&D.

The founder of SpacePharma states that the cost for a lab that fits on one of its 3U CubeSats is $60k (Yamin 2019). This cost is *exclusive* of the satellite itself and its launch.

They claim the full-up cost is $1 million, but this likely covers all of the operations, program management, and customer interaction. Within the 3U CubeSat, 1U is for the service module and 2U are pressurized volume for experiments (Amselem 2019). In other words, to host a similar experiment on an outpost would save about 1U-worth of hardware and associated launch costs.

Disposable Orbital Transfer Vehicle (d-OTV)

Some potential outpost customers do not require long durations in space for their activities. These potential customers might be satisfied by participating in a ride-sharing service with a SpaaS provider that uses disposable systems. Potential providers of such a service include Momentus, D-Orbit, and Xplore.



Source: Momentus Website

Figure A-7. Example of a d-OTV Provider Offering SpaaS

The Momentus Vigoride is advertising its d-OTV as also providing SpaaS, providing hosted payload with power, communications, and pointing. In January of 2019, Momentus announced its first contract (worth over $6 million) for a payload of up to 250 kg, or approximately $24,000 per kg (Momentus 2019).[52] A short time later, in April 2019, CEO Kokorich claimed the Vigoride service can deliver 300–400 kg to LEO and up to 100 kg to lunar orbit for a cost of around $4.8 million (Shieber 2019). In 2020, the Momentus website shows Vigoride's payload capacity rising to 750 kg (Momentus n.d.). Vigoride has a wet mass of 300–500 kg and can provide 1 kilowatt of power.

[52] This contract was subsequently cancelled; however, we use it for the purposes of analysis.

The cost of $6 million for 250 kg of payload includes the cost of the Vigoride hardware, and the launch costs associated with the approximately 400kg Vigoride vehicle and its 250kg payload. We estimate that the cost of the Vigoride hardware is approximately $2.75 million[53] and the cost of launching the vehicle, excluding the cost of launching its payload, is approximately $4.75 million.[54] Coincidentally, this is about the same price as quoted by Kokorich—perhaps his cost was for the vehicle only and did not include the costs associated with launching a payload. Based on this information, we estimate per-kilogram costs associated with launching payloads on this vehicle in Table A-5.

Table A-5. Cost Associated with Launching Payload on a d-OTV Vehicle in LEO

Element	Low Cost ($k/kg)	High Cost ($k/kg)
d-OTV [short duration]	6[a]	20[b]
d-OTV [long duration][c]	10	30

[a.] $4.75 million divided by 750 kg, rounded down

[b.] $4.75 million divided by 250 kg, rounded up

[c.] Using our factor of two heuristic for extending the lifetime of space vehicles, the hardware costs become $5.5 million per vehicle. Adding in the launch costs brings the total cost associated with a long duration Vigoride to approximately $7.5 million. The high and low costs per kilogram are divided by 250 kg and 750 kg respectively.

We assume that the cost of the operations while on orbit is negligible and thus the price of using this service is roughly independent of the length of time the payload stays hosted on the platform; i.e., whether the payload is actively hosted for a month or a year, the cost to Momentus is approximately the same.

We also assume that Vigoride can be used for launches to GEO. The ΔV from GTO to GEO is approximately 1.5 km/s, assuming no plane changes. According to Momentus, a Vigoride can provide up to 2 km/s of ΔV. Thus, we assume that a Vigoride can transport 200 kg of payload to a GEO orbit after a launch vehicle places it into GTO.

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53 This is the $6 million contract price minus the cost of launching the payload (250kg) and wet mass (400kg) at a cost of $5,000 per kg. We acknowledge that this launch cost, corresponding to a rideshare on a Falcon 9 to LEO, was probably not known at the time and may be an underestimate of the launch cost. However, using an underestimate of the launch cost gives a more conservative estimate of the cost of the tug.

54 The cost of the hardware ($2.75 million) plus the cost launching 400 kg at $5,000 per kg.

Table A-6. Cost Associated with Launching Payload on a d-OTV Vehicle in GEO

Element	Low Cost ($k/kg)	High Cost ($k/kg)
d-OTV [short duration]	15[a]	40[b]
d-OTV [long duration][c]	20	50

[a] Total cost to launch empty Vigoride with maximum wet mass (500kg) at $15,000/kg on Falcon 9 to GTO is $7.5 million. Adding the cost of the hardware ($2.75 million) brings the total to $10.25 million. We have generously assumed that the cost of the hardware for LEO is the same as for GEO. Finally, dividing by maximum payload mass of 750 kg yields $13,667/kg, which we have rounded to $15k/kg.

[b] $10.25 million divided by 250 kg, rounded.

[c] Using our factor of two heuristic for extending the lifetime of space vehicles, the hardware costs become $5.5 million per vehicle. Adding in the launch costs brings the total cost associated with a long duration Vigoride to approximately $13 million. The high and low costs per kilogram are divided by 250 kg and 750 kg respectively.

D-Orbit. Provides a "plug-and-play platform for on-orbit demonstration and validation." Payloads owners build their own CubeSat, up to 16U, which D-Orbit's InOrbit Now (ION) will deliver to a custom orbit or host the payload on the ION for the duration of the experiment. Each ION carries many payloads and can progressively drop payloads at various altitudes and planes, with launches going to LEO, SSO, and GEO every year. D-Orbit serves as the single contractual partner for the payload owner, handling frequency licensing, launch authorization, and flight readiness certification. All costs, including launch and operation costs, are bundled together and the customer is charged a flexible fee based on the services that they use. D-Orbit's promotional materials state that the price of a mission is "about a hundred thousand" dollars (D-Orbit 2020). It takes approximately 9 to 12 months from first contact with D-Orbit to launch. The company has already launched Doves for Planet and has at least three missions planned for 2021. D-Orbit has raised almost $30 million in investment, with about $18 million coming from the European Investment Bank (Werner 2020b).

Astro Digital. Very little information is publicly available about this company, but Astro Digital is reportedly to launch the Orbit Fab prototype. It provides "mission-as-a-service"—taking payloads from various payload owners, integrating and testing them, and operating the spacecraft (Werner 2020c).

RPO-enabled Orbital Transfer Vehicles (r-OTV)

After the payload is launched to space, it must be delivered to the outpost. This will require a vehicle that is capable of performing both orbital adjustments and rendezvous and proximity operations (RPO). We have already discussed cargo vehicles, which can perform this function; however, a more generic Orbital Transfer Vehicle (OTV) with RPO capability may be more appropriate for unpressurized or small payloads. There are approximately three options for where the RPO capabilities would reside in this more general situation. One option is to have an expensive OTV with RPO capabilities that delivers payloads to a relatively passive outpost. Another option is to use cheap and disposable OTVs to bring the payloads "near" the outpost and to allow the outpost to perform the necessary RPO to take the payloads from the relatively passive OTV. A final option would be a hybrid of the previous two approaches, in which a disposable OTV brings the payload "close" to the outpost and a small RPO-capable OTV is deployed from the outpost to pick up the payloads and return them to the outpost.

We roughly estimate the cost delta of adding RPO to a disposable vehicle by comparing the total cost of RESTORE-L/OSAM-1 with a rough estimate of a government-developed satellite that lacks RPO capabilities. The estimated lifetime cost of OSAM-1 is roughly \$600–\$800 million up to its launch readiness date (NASA 2020). This cost is assumed to exclude launch or mission operations. We know that the mission is using the SSL-1300 bus, which as previously described has a dry mass of approximately 900 kg and a payload capacity of about 500 kg. We assume the payload will be robotic arms, tools, and objects for assembly. QuickCost version 6.1 estimates the cost of such a mission with a 900 kg bus and 500 kg payload is about \$550 million, excluding launch and operations costs. Subtracting this from the total estimated cost of the mission yields about \$250 million in costs (\$800 million minus \$550 million). We use our rule of thumb that pure commercial development can achieve a factor of four savings compared to government-developed systems. Thus, the cost delta associated with RPO capabilities for a private company are assumed to be about \$60 million (250/4 rounded down) to get to the first flight unit. Using our factor-of-two heuristic for relating production unit and development costs, that means the cost for a unit is \$20 million and the development cost is \$40 million.

Using this cost delta, we roughly estimate a high and low-cost option for a reusable RPO-enabled tug (Table A-7). The high-cost estimate uses an SSL-1300 bus (\$125 million), two arms (high cost of an arm at \$60 million each), and RPO capabilities (\$60 million); this is approximately \$305 million. The low cost estimate uses the Saturn-class X-sat bus (\$5 million), two arms (low cost of an arm at \$15 million each), and RPO capabilities (\$20 million); this is \$55 million. As we have neglected the development costs of RPO capabilities, integration costs, and operations costs, this is likely a lower bound on the cost. For context, Roesler (2020) estimates the cost of an RPO-capable tug with two arms at \$100–\$200 million. Our lower estimate is below his and our higher estimate is above his.

Table A-7. Unit Cost Estimates Associated with r-OTVs

Element	Units	Low Cost [$k]	Low Mass [kg]	High Cost [$k]	High Mass [kg]
Bus	1	5,000	150	125,000	4,700
Arm External	2	30,000	150	120,000	150
RPO Capability	1	20,000	-	60,000	-
Subtotal		**55,000**	**300**	**305,000**	**4,850**
Launch to LEO ($5k/kg)		1,500		24,250	
Total[a]		**60,000**		**330,000**	

a. Rounded up to one or two digits.

To model RPO capabilities for an r-OTV (not a cargo vehicle) requires a full accounting of many factors that we cannot know a priori. Specifically, the cost of the trip will depend on the number of customers it has, the propellant required to make the necessary journeys for its customers, the amount of propellant on board the tug, the efficiency of its engines, and the costs/benefits associated with refueling. Rather than attempt to account for all of the complexities associated with in-space logistics, we produce a rough heuristic based on the lifetime number of customers without refueling. We also assume that the vehicle is capable of ferrying 300 kg per trip. Using these two assumptions, the lifetime cost of the r-OTV can be amortized over its user base and a cost-per-kilogram can be generated (Table A-8).

Table A-8. Cost per Kilogram Associated with RPO-capable Tug Journey

Lifetime Transits of Tug[a]	Low Cost[b] ($k per kilogram)	High Cost[c] ($k per kilogram)
1	200	1100
5	40	220
10	20	110
20	10	55
30	7	37
40	5	28
50	4	22

Note: All cost numbers are rounded to one or two digits.

a. Each transit is assumed to carry 300 kg of payload. For 10 transits over the lifetime of the r-OTV, that is 3,000 kg of total mass delivered.

b. Total system cost of $60 million. For 10 transits, divide the system cost by 3,000 kg.

c. Total system cost of $330 million. For 10 transits, divide the system cost by 3,000 kg.

For the purposes of our analysis, we will assume that the vehicle operates for 10 years and has approximately 1 mission per year, for a total of 10 transits in its lifetime. Rounding slightly in Table A-8, we choose $20,000 per kilogram for the low-cost estimate and $110,000 per kilogram for the high-cost estimate. While we use these estimates for our analysis, we are skeptical that 10 transits could be accomplished on a single load of propellant; though it may be possible if the drop-off point is close to the outpost and the r-OTV conducts most of its business "near" these orbits. These costs are in addition to the cost-per-kilogram associated with the launch vehicle.

An important caveat is that—using these assumptions—the outpost likely needs to be *very* close to the drop-off orbit in LEO. If we assume that the RPO tug carries 300 kg of payload on every trip to the outpost and that payloads are 50 kg each, then each time the tug is used it carries 6 customers. If 60 to 240 customers are needed to break even, that corresponds to 10 to 40 trips the tug must make over an orbital lifetime of 10 years. It will be challenging to design a tug that can survive in space for a decade and make 40 round-trip journeys on a single tank of propellant. The addition of in-space refueling is beyond the scope of the current analysis; however, it could potentially enable the needed performance for the in-space tug.

We do not directly calculate an estimate for an r-OTV in GEO. Instead, we note that the cost of using a d-OTV in GEO is approximately twice the cost of using a d-OTV in LEO. We apply the same heuristic to our costs for the r-OTV; costs per kilogram double from the trip in GEO.

Traditional ISS-like Modules

For this analysis, we assume that all traditional modules have an internal volume of 330 cubic meters. For our high-cost scenario, we use cost estimates of an ISS module. We construct a low-cost estimate based on the now-defunct Bigelow habitat.

A stripped down ISS module without subsystems is estimated to cost about $270 million[55] and has an internal volume of 155 m3 (Crane et al). This is about 1.7 million per cubic meter. An ISS-heritage module is estimated to weigh 15,900 kg (NASA 2017), which is approximately 100 kg per cubic meter. Other subsystems are estimated to cost about $270 million and have a mass of 3,100 kg (Crane et al).[56] We do not include a cost for

[55] The reference reports the cost as $250 million in 2015 dollars. Accounting for inflation, we convert into 2020 dollars and round to two digits.

[56] Crane et al. report that the ADCS, power, TT&C, communications, and propulsion systems cost about $246 million in 2015 dollars.

ECLSS because this is a purely uncrewed platform. Table A-9 shows our estimate of the hardware and launch costs of a high-cost station.

An expandable module like the Bigelow 330 may cost about $330 million[57] and has 330 cubic meters of pressurized volume (Crane et al). This module may have a mass of approximately 20,000 kg (Bigelow Aerospace 2016). We use the same mass and cost for the other subsystems as in the high-cost estimate.

Table A-9. Hardware costs of a traditional space station module

Element	Units	Low Cost [$m]	Low Mass [kg]	High Cost [$m]	High Mass [kg]
Bus	1	300	20,000	528	33,000
Other Subsystems	1	270	3,100	270	3,100
Total		**570**	**23,100**	**798**	**36,100**

57 The reference reports the cost as $300 million in 2015 dollars.

Appendix B.
Analysis of Potential iSDT Payloads

SMC's Test Candidate List

Heuristics for Analyzing the List

The DoD Space and Missile Systems Center (SMC) has gathered a list of approximately 150 potential payloads that they propose as candidates for in-space developmental testing. Not all of these payloads in the list necessarily require in-space testing or, further, the use of an orbital outpost. For our analysis, we prune the list by removing all candidates that do not appear to be strong candidates for an outpost. While not fully comprehensive, we assume that the remaining payloads in the list are approximately representative of the types of systems that may be tested in space.

To prune the list, we assume that a space-related capability **is not** suitable for in-space testing on an outpost if it:

- tests an integrated system (e.g., a CubeSat or prototype of a satellite);
- can only be performed on an isolated system, like new reaction control hardware (e.g., gyroscopes) or algorithms;
- requires multiple payloads simultaneously (e.g., satellites performing RPO, formation flight, space-to-space comms/crosslinks, satellite servicing);
- tests ground-based capabilities (e.g., terrestrial SSA assets track small maneuvering objects);
- tests software products that do not clearly call for in-space testing;
- tests de-orbit devices (e.g., drag sails); or
- is an analytic product (e.g., designing a new orbit like Parker Transfer, analyzing modular architectures for hardware and software).

Of the remaining payloads, we identified approximately 17 different categories of capabilities. Of payloads that might leverage an orbital outpost, only about 40 of the entries in the list contained technical specifications that would allow us to generalize the masses, power levels, and test durations of the payloads.

We classify the remaining payloads according to their capability type, mass, power, minimum test duration, required orbit, pressurized volume, and logistics tail (e.g., up- and down-mass requirements). In doing so, we make the following assumptions:

- Mass has a lower bound of 1 kg and is unconstrained on the upper bound;
- Power is quantized into 1W, 10W, 50W, 100W, 500W, and 1000W levels, with payload power always rounded up;
- Test durations are quantized into: Quick Test lasting 0.25 year; Normal Test lasting 0.5 year; Long Test lasting 1 year; and Extra Long Test. Many entries in the test spreadsheet indicated test lengths that stretched many years; we label these as Extra Long Tests and collapse them down to long tests of 1-year duration. For test length, we always round down;
- The orbital environment for test payloads is segmented into four rough divisions.
  - ISS: Some payloads can be tested on the ISS.
  - LEO: All other orbits in LEO that are not the ISS. This includes Sun-synchronous orbits and is appropriate for any payloads that need to reach above 400 km altitude.
  - GEO: Some payloads may need to be tested in GEO orbits or higher.
  - Any: The payloads indicated that they can perform their test in any orbit.
- Unless mentioned explicitly, payloads are assumed to have zero up-mass and down-mass requirements.
- None of the payloads in the SMC list requires pressurized volume.

Potential Test Articles

Battery. We identified three payloads that sought to test novel battery concepts in space, all of which were very low mass. We assign all battery tests an approximate mass of 1 kg. Only two of the payloads revealed power requirements; we assign all battery tests as requiring 10W. Length of test provided was years; we assign all battery tests a long-term test duration. Suggested missions were for GPS (MEO), GEO and xGEO (pole-sitter orbits); however, spreadsheet indicated that any orbit would work for the test.

Beacons. We identified one payload to test low SWAP satellites beacon technology. We assign all beacon tests as using 1 kg of mass and 10W of power. Normal test length and can be tested in LEO.

Clocks. We identified a single potential payload for improving timing performance for PNT applications. It appears to need only "space qualification" which could be satisfied by ground tests. Regardless, we include it in our list of potential payloads. No technical specs are provided, so we use the specs from the Deep Space Atomic Clock (DSAC) experiment flown in 2019: 20 kg and 50W. This is reasonable as briefing of the clock experiment contains pictures of a GPS atomic clock that roughly matches the scale of the DSAC. We note that DSAC was flown on the Orbital Test Bed 1 (OTB-1) satellite, which is at approximately 720 km. Thus, while these clocks may ultimately be used for GPS satellites, they can be tested in LEO.

Communications. We identified at least 10 potential tests for communication systems. We segment them into two categories.

- Comms (GEO). These are large payloads that may need to be tested in GEO. We assign a mass of 80 kg, power at 1,000W, and a long test length.
- Comms (LEO). These are small payloads that can be tested in LEO. We assign a mass of 10 kg, power of 50W, and a short-duration test length.

Computing. We identified three tests that were focused on on-orbit computing. We assign a computing payload a mass of about 20 kg and requiring about 50W of power. These tests are assumed to be of normal length and can be performed in LEO.

Cryogen Management. We identified one test (RRM3) that was focused on in-space cryogenic propellant management; this test was flown on the ISS. We are unable to determine the mass of the full experiment; however, it contained approximately 19 kg of cryogenic methane and appears to be size of a household refrigerator. Based on this, we approximate the mass as about 150 kg. The test attempted to prove zero-boil off in space; assuming this was done with active cooling, the power requirements are likely in the 100s of watts. We assign approximately 500W as the power requirement for such an experiment. The test was of normal length.

Deployable Systems. We identified two payloads that test deployable structures, such as the Roll-Out Solar Array (ROSA) experiment that was tested on the ISS; however, neither of the payloads provided mass or power specifications. We believe that the ROSA deployable solar array was designed to provide 20kW of power (p5 of ref). Assuming that the solar cells had a specific power of about 150 W/kg (p11 of ref), we estimate the payload would have a mass of about 150 kg.[58] The test had a lifetime of only about 2 weeks before being jettisoned; thus, test lengths for deployable structures are likely to be quick. Lacking an estimate for the power required to unfurl the solar array, we assign a power requirement of 100W.

The ROSA test offers insights into the potential operations of an orbital outpost. First, we note that the deployable solar array was unable to retract as designed. This partial failure

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[58] 20,000 Watts divided by 150 Watts/kilogram is 133 kg. We round up to 150 kg.

caused the payload to be jettisoned from the ISS, rather than stowed in the trunk of the returning SpaceX Dragon capsule for immediate reentry. This suggests that deployable structures are potentially only suited for testing in low LEO, where such a failure can be mitigated by a similar jettison maneuver.

Alternatively, assume that ROSA successfully demonstrated the ability to generate 20kW of power. If the ROSA experiment had taken place on an orbital outpost, it need not necessarily be detached after the test is concluded. The outpost operator could potentially buy the payload from the customer and harvest the power to sell to other outpost customers that have high-power needs. As 20kW is far more power than many of the proposed outpost designs are planning to provide, such an arrangement may open new potential applications and opportunities. We do not analyze such a scenario, however, because thermal, power, and station-keeping management capabilities of the outposts would need to be substantially improved to incorporate such a large infusion of power generation capacity.

Directed Energy Resilience. We identified two payloads that were focused on detecting and mitigating damage to directed energy attacks. Based on the descriptions of the tests, we tentatively believe that the test can be safely performed on a shared platform. Neither payload provided a mass or power specification.

Electric Propulsion. We found one payload seeking to test an electric propulsion system. Based on this payload, we assign all electric propulsion tests as having about 10 kg of mass and 500W. At these power levels, the force of the propulsion system is likely to disturb the orbit and potential operations of other hosted payloads aboard the outpost. For instance, payloads that use sensitive optics would be damaged by deposition of rocket exhaust onto their surfaces. Similarly, propulsion tests would create forces on the outposts that could ruin payloads that use microgravity. We make the optimistic assumption that such considerations can be alleviated by scheduling payloads, potentially requiring multiple outposts; however, this scheduling may increase times to flight for payloads. Due to these scheduling constraints, we assign electric propulsion tests as being quick.

Interfaces for Docking, RPO, and Satellite Servicing. We identified one payload that tests a docking interface. Such an interface is designed to facilitate the capture of objects and provide services such as power and data across the interface. Such a docking device could be used to chain various outpost building blocks together or could be used to attach payloads to buses in a general SpaaS architecture. Each interface appears to be about 3 kg and two interfaces would be needed for a single test, bringing the mass of the test article to 6 kg. The payload would test power transfers of approximately 500W.

Lasers. Two payloads listed, one has already flown, no data given for the other.

Power Generation. One payload listed, which is a solar array for Nanosats. No other data given.

Sensor – Infrared Radiation. Spreadsheet indicates a desire for testing of sensors that may feed into SBIRS. We could not attribute specifications for such a sensor.

Sensor – Meteorology. Most of the payloads listed are CubeSats, 12 U and bigger. Some of the listed payloads indicate that they do not need testing; for instance, briefings regarding the CHISI satellite make the case that its technology is already TRL 9 (Fisher 2019).

Sensor – Remote Sensing. We found one payload seeking to test novel remote sensing capabilities. The payload has a mass of 45 kg and requires up to 100W of power. The test can be performed in any LEO orbit and would be of long length.

Space Weather R&D. We identified four payloads. Based on the specifications for one of the hosted payloads, we assign all such payloads a mass of 15 kg and 50W. As these instruments are gathering data, they will stay for 3–5 years. All payloads in the database required an orbit in low LEO, but above the altitude of the ISS.

Space-based SSA. Spreadsheet indicates a desire for testing of sensors related to space situational awareness. We could not attribute specifications for such a sensor.

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Abbreviations

3D	three-dimensional
ABI	Advanced Baseline Imager
ADACS	Attitude Determination and Control System
AIRS	Atmospheric Infrared Sounder
AMF	Additive Manufacturing Facility
AMS	Alpha Magnetic Spectrometer
BFF	BioFabrication Facility
CASIS	Center for the Advancement of Science in Space
CHISI	Compact Hyperspectral Infrared Sounding Interferometer
CLD	Commercial LEO Destinations
CondoSat	condo satellite
CONOPS	concept of operations
COTS	Commercial Orbital Transportation Services
CRS	Commercial Resupply Services
DACIS	Defense and Aerospace Competitive Intelligence Service
DARPA	Defense Advanced Research Projects Agency
DHS	U.S. Department of Homeland Security
DIU	Defense Innovation Unit
DoD	U.S. Department of Defense
DOE	U.S. Department of Energy
d-OTV	disposable orbital transfer vehicle
DSAC	Deep Space Atomic Clock
ECLSS	environmental control and life support services
EELV	Evolved Expendable Launch Vehicle
ESPA	EELV Secondary Payload Adapter
FCC	Federal Communications Commission
FOMS	Fiber Optics Manufacturing in Space
GaN	gallium nitride
GEO	geosynchronous
GLM	Geostationary Lightning Mapper
GOES	Geostationary Operational Environmental Satellite
GRASP	Grapple, Retrieve, and Secure Payload
GSFC	Goddard Space Flight Center
GTO	Geosynchronous Transfer Orbit
HSB	Humidity Sounder for Brazil
IDA	Institute for Defense Analyses
ION	InOrbit Now
ISO	International Organization for Standardization

ISS	International Space Station
ISSNL	International Space Station National Laboratory
JCIDS	Joint Capabilities Integration and Development System
JROC	Joint Requirement Oversight Council
JWST	James Webb Space Telescope
LEO	low-Earth orbit
LMIRIS	Lockheed Martin Infrared & Imaging Systems
mbps	megabit per second
MDL	middeck lockers
MEO	medium-Earth orbit
MLE	Middeck Locker Equivalent
MMS	MultiMission Modular Spacecraft
MUSS	Multi-User Systems and Support
NASA	National Aeronautical and Space Administration
NIST	National Institute of Standards and Technology
NOAA	National Oceanic and Atmospheric Administration
NOM4D	Novel Orbital and Moon Manufacturing, Materials and Mass-efficient Design
NSR	Northern Sky Research
ODMSP	Orbital Debris Mitigation Standard Practices
OSAM	On-orbit Servicing, Assembly, and Manufacturing
OSTP	Office of Science and Technology Policy
OTB-1	Orbital Test Bed 1
OTV	Orbital Transfer Vehicle
PNT	positioning, navigation, and timing
POC	Physical Optics Corporation
R&D	research and development
ROSA	Roll-Out Solar Array
r-OTV	reusable orbital transfer vehicle
RPO	rendezvous and proximity operations
RSDO	Rapid Spacecraft Development Office
RSGS	Robotic Servicing of Geosynchronous Satellites
RSV	robotic servicing vehicle
SaaS	space-as-a-service
SBIR	Small Business Innovation Research
SDA	Space domain awareness
SiC	Silicon carbide
SMC	Space and Missile Systems Center
SpaceFORM	Space Facility for Orbital Remote Manufacturing
SPDM	Special Purpose Dexterous Manipulator
SSA	space situational awareness
SSO	Sun-synchronous orbit
STP	Space Test Program
STPI	Science and Technology Policy Institute
TRLs	technology readiness levels
TT&C	telemetry, tracking, and control

TTPs	tactics, techniques, and procedures
U	units
USAF	U.S. Air Force
USSF	U.S. Space Force

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14. ABSTRACT
Government agencies and private companies have recently expressed interest in the development of an uncrewed, persistent platform in space. The Department of Defense (DoD), through the Defense Innovation Unit (DIU), has funded several projects to create such platforms, which they call orbital outposts. DIU has also funded the development of multi-orbit logistics capabilities that would support such an outpost. An outpost could potentially support government, industry, and academic needs for in-space testing of space systems, refreshing technologies on operational satellites, microgravity research and development (R&D), in-space manufacturing and assembly of products, deployment of space assets more rapidly than possible using launch vehicles, and other applications. The purpose of this study is to assess the feasibility and potential cost-effectiveness of using orbital outposts, as opposed to alternative methods for access to space, to support a variety of these use cases.

15. SUBJECT TERMS
Access to space; Microgravity; Modularity; On-orbit servicing, assembly, and manufacturing (OSAM); Persistent Platform; Satellite-as-a-Service; Space; Space Robotics; Space Tug; Space-as-a-Service

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