AIAA 2017-5360
AIAA SPACE Forum
12 - 14 Sep 2017, Orlando, FL
AIAA SPACE and Astronautics Forum and Exposition

# Feasibility Analysis of Commercial In-Space Manufacturing Applications

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**Though in its infancy, In-Space Manufacturing (ISM) has the potential to be a paradigm shifting technology allowing for increased access to and exploration of space. ISM yields several benefits over the traditional Earth-build-and-launch approach. Most importantly, it removes launch considerations – including schedule, risk and strenuous loads and vibrations – from the component or system design process. As any new space venture can be a costly and risky endeavor, it would be prudent to understand which applications of ISM are viable and promising candidates for the commercial sector to invest in. This paper investigates the commercial feasibility of several potential applications of ISM through a series of case studies: ISM of antenna reflectors, ISM of solar panel support structure, and ISM of spare parts for long duration space missions. The studies quantified the sensitivity of the business cases of these applications to a variety of factors including ISM capability development cost, technical parameters of the component or system being built, and reliability of economic forecasting of the space sector. This paper also provides recommendations for strategic investments by both NASA and private partners to maximize the future potential and impact of ISM.**



## Nomenclature

| | | |
|---|---|---|
| $A$ | = | solar panel area, $m^2$ |
| $A_{BE}$ | = | breakeven array area, $m^2$ |
| $A_{cell}$ | = | area per solar cell, $m^2$/cell |
| $c_{cell}$ | = | solar cell unit cost, \$/cell |
| $c_{GEO}$ | = | launch cost per kg to GEO, \$/kg |
| $c_{matl}$ | = | material cost per kg, \$/kg |
| $C_{cells}$ | = | solar cell cost, \$ |
| $C_{facility}$ | = | ISM facility cost, \$ |
| $C_{facility,max}$ | = | maximum allowable facility cost, \$ |
| $C_{struct}$ | = | structural material cost, \$ |
| $C_{total}$ | = | total solar array system cost, \$ |
| $M_{cells}$ | = | solar cell mass, kg |
| $M_{dep}$ | = | deployment mechanism mass, kg |
| $M_{dep,ISM}$ | = | deployment mechanism mass for ISM arrays, kg |
| $M_{dep,launch}$ | = | deployment mechanism mass for launched arrays, kg |
| $M_{struct}$ | = | panel structural mass, kg |

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| | | |
|---|---|---|
| $M_{total}$ | = | total solar array mass, kg |
| $N_{cells}$ | = | number of solar cells |
| $P$ | = | power required, W |
| $\alpha$ | = | areal density of structural support |
| $\alpha_{cells}$ | = | solar cell areal density, $kg/m^2$ |
| $\alpha_{ISM}$ | = | areal density of ISM solar arrays, $kg/m^2$ |
| $\alpha_{launch}$ | = | areal density of launched arrays, $kg/m^2$ |
| $\epsilon$ | = | solar cell packing efficiency |
| $\eta$ | = | solar cell efficiency |
| $\theta$ | = | angle between panel normal and sun vector |
| $\lambda$ | = | structure areal density, $kg/m^2$ |
| $\lambda_{launch}$ | = | effective areal density for launched arrays, $kg/m^2$ |
| $\mu$ | = | ratio of ISM to launch deployment mechanism mass |
| $\nu$ | = | ratio of ISM to launch structural support areal densities |
| $\phi$ | = | solar irradiance, $W/m^2$ |
| $\omega$ | = | ratio of boom to panel width for flexible arrays |

| | |
|---|---|
| AMF | Additive Manufacturing Facility |
| DARPA | Defense Advanced Research Projects Agency |
| ECLS | Environmental Control and Life Support |
| EPS | Electrical Power System |
| GEO | Geosynchronous Earth Orbit |
| IMLEO | Initial Mass in Low Earth Orbit |
| ISM | In-Space Manufacturing |
| ISRU | In-Situ Resource Utilization |
| ISS | International Space Station |
| LEO | Low Earth Orbit |
| POS | Probability of Sufficiency |
| RDTE | Research, Development, Test, and Evaluation |
| RF | Radio Frequency |
| RSGS | Robotic Servicing of Geosynchronous Satellites |
| TFU | Theoretical First Unit |
| TUI | Tethers Unlimited, Inc. |

## I. Introduction

As NASA seeks to establish a presence on other bodies in the solar system, the private sector ensures continued access to near-Earth space via a variety of commercial space services.[1] In-Space Manufacturing (ISM) has the potential to accelerate and expand such access while also enabling key technologies for long duration human exploration of the Moon, Mars, and beyond. The promise of ISM is two-fold. First, it can provide alternative means for delivering goods and services to space systems apart from the traditional launch industry, which can be expensive, risky, and subject to delays. This also eliminates launch-based constraints on space system design such as size limits due to fairing dimensions and large acceleration loading requirements.[2] Second, when coupled with other technology such as In-Situ Resource Utilization (ISRU), ISM could allow for reduced reliance on Earth for mission logistics such as spares and repair equipment. ISM will enable cheaper, faster, and more sustainable systems in the new space economy. As such, ISM has the potential to enable new business opportunities and profitable economic activity in space.

Indeed, ISM is one of the budding industries within the new commercialization of space. Already we have seen a public-private experiment onboard the International Space Station (ISS), in which NASA and Made in Space, Inc. demonstrated the efficacy of additive manufacturing in space.[3] When investigating commercial potential of private ISM capabilities, a methodical approach is required which can frame the problem and reveal key metrics for profitability. This paper will investigate the strategic development of profitable ISM enterprises by building a modeling framework to examine potential markets and identify the conditions that most effectively lead to a healthy ISM economy.

## II. Background and Motivation

### A. Defining In-Space Manufacturing

The first step towards a strategic framework for investigating ISM is to properly define the term. The analysis undertaken for this paper followed closely the definition of ISM proposed by Skomorohov which states that ISM encompasses any endeavor which takes place outside of the Earth's atmosphere and which performs any of these three activities:[4] fabrication, assembly, and integration. Fabrication can be defined as a process which converts raw material into a component through some industrial method – for example, 3D printing solar panels. Assembly is the process of joining fabricated or delivered components into a higher level component which could include a spacecraft subsystem – for example, joining the 3D printed solar panel with a stock of solar cells and wiring to form a functioning solar array. Integration could be seen as the mating of the new component or subsystem into the larger system, usually the spacecraft, in such a way that the whole system functions together as intended. In the given example, integration would include installing the solar array onto a waiting spacecraft and incorporating it with its power system.

While ISRU could fall under the definition of ISM (as "fabrication" of raw material stock from mined or extracted resources), the authors chose to exclude it from the definition for this analysis. ISRU is a rich and active field of research and has potential commercial applications in its own right. In combination with ISM, it could prove extremely useful; in fact, one of the case studies, presented later, looked briefly at such a union of the two. However, the authors found it prudent to focus the scope of analysis on fabricated spacecraft or subsystem components which can more directly stimulate a near-term, near-Earth space economy.

#### *1. In-Space Manufacturing Technologies*

ISM, as defined previously, is an umbrella term for a variety of technologies, processes, and architectures which deliver a desired component or system to a spacecraft outside of the traditional Earth-launch paradigm. Of particular interest within the fabrication regime of ISM is additive manufacturing, or 3D printing. Additive manufacturing is a budding industrial manufacturing approach and has become one of the first to be demonstrated in space; in 2016, the Additive Manufacturing Facility (AMF) onboard ISS began making parts out of extruded plastic feedstock and as of April 2017 it has made nearly 40 parts for various purposes including test articles, spare parts and medical equipment.[5] It is envisioned that in the near future, metal 3D printers will be demonstrated in space which will be able to produce structural elements, repair parts and even entire satellites.[6] More traditional manufacturing methods such as welding, casting, and "subtractive" methods have seen little practical adaptation to space applications to date.

The extent of most demonstrated ISM has fallen under the fabrication regime. Assembly and integration of space manufactured components has been limited to the tests conducted by ISS astronauts on parts made by the AMF. Crew time and ingenuity could be used in conjunction with ISM for use cases such as repair, maintenance and assembly of stations. However, as astronaut time is extremely valuable, a truly commercially viable ISM technology would limit its need for crew presence. These more advanced, uncrewed concepts such as remote satellite servicing and installation require significant investment in the robotic and spacecraft infrastructures and technologies to become a reality. The most ambitious of these advanced concepts propose free-flying facilities capable of receiving orders for components, manufacturing them, and delivering and installing them to client spacecraft in an entirely automated fashion.

The following are just some of the more advanced ISM concepts which have been recently proposed. Tethers Unlimited, Inc. under contract with NASA is pursuing work on their SpiderFab and MakerSat mission concepts;[7,8] these projects aim at a free-flying CubeSat based construction of large truss structures for use as long-baseline apertures and structural components of large space assemblies. Similarly, Made In Space's Archinaut concept proposes to 3D print and deliver via robotic arms large aperture antenna reflectors to client spacecraft; the 3D printer is designed to either be a self-contained free-flying facility or attached to existing spacecraft such as a space station.[9] Also, the Defense Advanced Research Projects Agency (DARPA) has entered into a contract with Space Systems Loral to develop the Robotic Servicing of Geosynchronous Satellites (RSGS) program: a spacecraft capable of manipulating, inspecting, repairing and upgrading satellites in Geosynchronous Earth Orbit (GEO).[10] Lastly, NASA's Restore-L mission proposes a similar satellite servicing technology demonstration including precision docking, grasping, manipulation and repositioning of target satellites.[11] While DARPA's RSGS and NASA's Restore-L do not explicitly involve fabrication, assembly or integration of components, their remote and robotic servicing capabilities are critical in enabling the technology necessary for future free-flying ISM facilities.

With recent commercial and government interest in ISM established, the case studies presented in this paper assume that such an ISM system is possible and exists. It is assumed that the ISM system is capable of fabricating, assembling and integrating components of interest to customer spacecraft. Detailed design of such a facility along with specific manufacturing and robotic technologies needed are kept out of the scope of this analysis. With this assumption, we create a parametric model for each case study incorporating major ISM considerations which identifies characteristics and breakpoints of a successful commercial ISM facility.

*2. ISM Benefits and Challenges*

The value of ISM, and therefore the viability of an ISM economy, depends upon the benefits that could be gained by the adoption of ISM over a traditional Earth-launch paradigm. A review of previous literature which included claims from early players in the ISM industry was conducted to identify these benefits. A high level characterization yields three primary benefits:

- *Component Design* - the ability to create designs which would be infeasible when paired with traditional launch delivery.[2,12,13]
- *Responsivity* - the ability to react to changes in the needs of space-based systems that is more efficient than before.[2,12,14,15]
- *Manufacturing Methods* - benefits from the manufacturing techniques most likely to be adopted by the ISM industry and their interactions with the space environment[13,14]

The same categorization can be used to analyze the many challenges that will be faced by the ISM industry. Table I summarizes specific benefits and challenges that fall under this categorization.

**Table I. Non-exhaustive survey of potential benefits and challenges of In-Space Manufacturing.**

| | **Benefits** | **Challenges** |
|---|---|---|
| **Component Design** | Component size no longer constrained by launch vehicle fairing constraints | Must design for limited to no human presence in the manufacturing/assembly process |
| | Component structural mass savings of up to 30% due to avoided launch load constraints[2] | Must design to available materials; sacrifice highly specialized materials for common feedstock |
| **Responsivity** | Delivery times for components reduced to only manufacturing/testing time – not dependent on launch schedules | Lack of space-based, remote testing, verification and validation of component design and manufacture could lead to less reliable parts |
| | Allows greater Earth-independence for long duration missions, especially with ISRU | Communications constraints on component build instructions for components designed on Earth |
| | Satellite servicing to extend lifetime or recover failed satellite | |
| **Manufacturing Methods** | Feedstock/raw material more efficiently packed for launch than Earth-built component | High power and thermal dissipation requirements for manufacturing methods |
| | Some techniques, like 3D printing, can benefit from zero-g environment (e.g. no need for supports on overhanging edges) | Highly stable surface required for manufacturing; potential interference with spacecraft dynamics |
| | | Fluid flow, surface tension and floating particulate issues from zero-g environment |

## III. Methodology

The potential benefits discussed above allow for a wide range of applications of ISM for space-based and terrestrial customers. Existing literature has identified these applications, mainly for the Earth-based satellite market. Past analyses of these applications has remained at a high level and only identified promising candidates.[4] Little work has been done on determining the technical and economic conditions which make viable business cases of these candidate applications. The work presented in this paper investigates, through a series of case studies, the circumstances needed for a profitable ISM economy and makes policy and technology recommendations which can realize such an economy. We analytically bound the potential benefits of ISM applications for both Earth orbit and deep space missions.

The literature review identified an especially promising sector of a future ISM economy: large space structures for commercial satellites. Two of the three case studies presented fall within this category. The first investigates ISM as applied to communications subsystems, namely antenna reflectors; the second performs similar analysis on the power subsystem with ISM of solar panels. The third case study explores ISM of spare parts for long duration missions in Earth orbit, building upon previous work investigating ISM applications for deep-space missions.[14,16,17] Key metrics including mass and cost of investigated subsystems are approximated using validated parametric models. The analysis takes into account the strong coupling between subsystems of space vehicles (e.g. communications and power). System costs are decomposed into research development test and evaluation (RDTE), theoretical first unit (TFU), and launch.[18] Launch costs are calculated using initial mass in low Earth orbit (IMLEO) and are taken from cost-per-mass estimates provided by launch providers.[19]

The assumptions on parameters and constraints used in the models are discussed. No assumption is made regarding how ISM is implemented, only that such a capability exists. Possible options are a free-flying uncrewed facility, ISS-based facility, or production facilities located on Lunar or Martian bodies. For those cases enabled by ISRU,[20] the cost of collecting and refining the source material is also not evaluated in this study. The potential business case of the ISM capabilities can then be determined as the net of the benefits (presented here) and the ISM system implementation cost (dependent upon the particular implementation and technology development cycle, beyond the scope of this analysis). This puts a bound on the cost at which ISM proves feasible under the assumptions of this analysis.

## IV. Case Study 1: Antenna Reflector Manufacture

The desire for increased satellite data-rates for both telecommunications and exploration missions drives the need for larger antenna reflectors and increased transmit power. Reflectors are constrained by requirements of payload geometry and launch loads. The ability to provide larger antenna reflectors in-space post-launch as an alternative to deployables is a potential valuable business opportunity which enables increased cost-effectiveness[2,4]

Thus, we investigate ISM-based antenna reflectors for Radio Frequency (RF) communication for multiple destinations. The study captures the new design opportunity and ISRU benefits of ISM. Analyses include three mission types: GEO broadcast, Low Earth Orbit (LEO) small-satellite downlink, and exploration of Mars. For each mission, two ISM strategies were compared to the baseline case without ISM. The first, Earth-based ISM, models a strategy where antennas are produced in space by an independent facility using materials brought from Earth; the second, ISRU-based ISM, includes the capability of using material sourced at the mission destination, reducing the launched mass.

System sizing of both the communications and power systems was used to determine total impact of ISM-based antennas on cost of the system. The communications system is further decomposed into reflector and transponder subsystems. Sizing was accomplished using link budget relationships and existing parametric mass models presented in Wertz, 2011.[18] The cost of each subsystem was calculated – RDTE, unit production, and launch of initial mass in LEO based on the parametric USCM 7th Edition cost models.[18] Assumptions for each case are presented in Table III of the Appendix.

A standard Earth-launch approach was used as the baseline against which the benefits of ISM could be compared. The maximum benefit provided by ISM is found by identifying the minimum cost system to produce. The optimum antenna diameter is determined by finding the minimum cost power and communication system for each case. For the ISM cases, the unit production cost is beyond the scope of this analysis, as discussed in Section III; as a result, the unit production cost in these cases is set to zero, and should be considered as part of the cost of implementing ISM which must be balanced against the benefits presented here. For the ISRU case, the launch cost is assumed to be zero to represent the ability to use material which is already in space.

Figure 1 below shows the relationship between communications / Electrical Power System (EPS) cost and antenna diameter. Approximate rigid and deployable antenna maximum diameters are given.[21,22] These results show that the cost savings per reflector from ISM when compared to the baseline increases with the communication distance. The combination of increasing transportation cost and free space path loss contribute to the need for a combination of more capable power and communication system. The possibility of producing very large diameter antennas (and thus larger gain and effective radiated power) in space for low costs drives the savings of ISM in these cases. An ISRU capability combined with ISM provides the most savings for these cases with larger transportation costs.

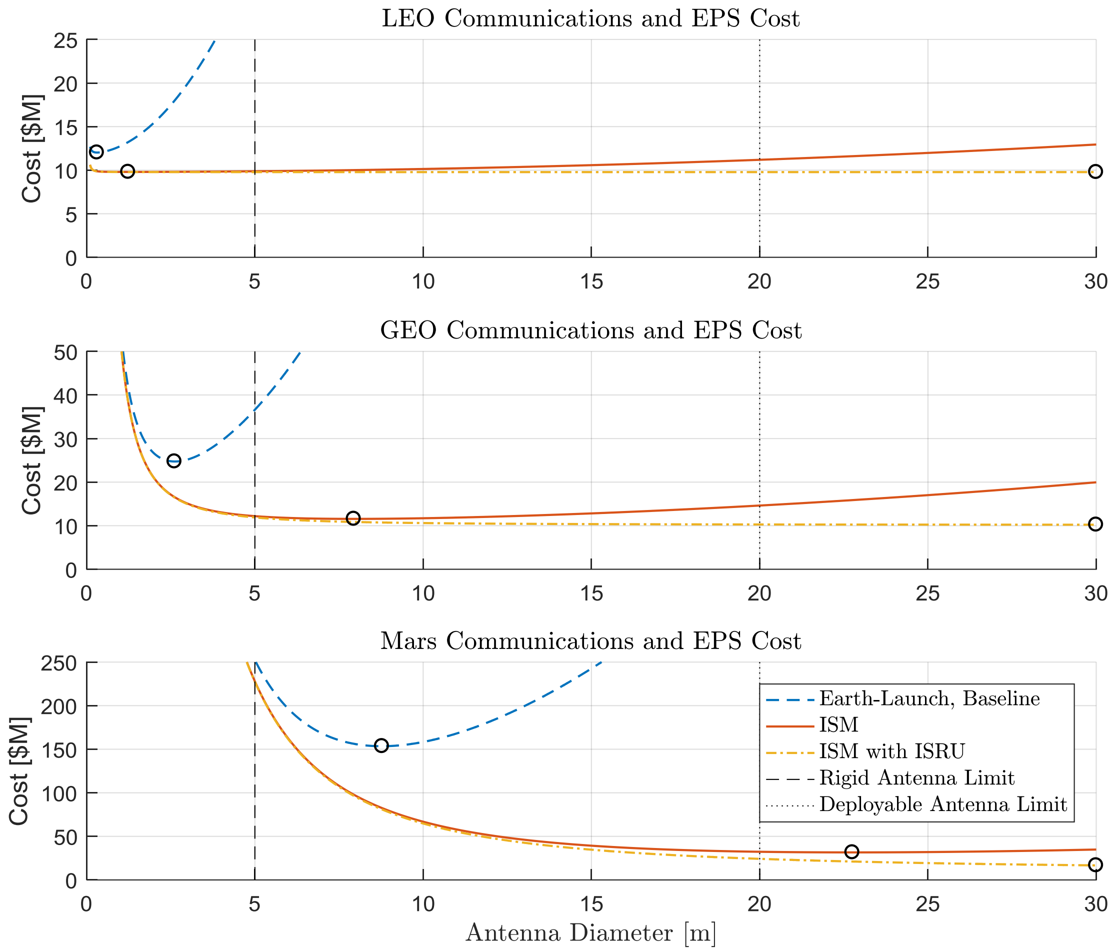


**Figure 1. Relationships between combined communications/EPS cost and antenna diameter for LEO, GEO, and Mars communication cases.**

The maximum total savings to the satellite industry is determined by extrapolating these savings based on the expected number of future antennas needed. For reference, an approximate ten year forecast of satellite market size is given assuming that annual satellite demands remain constant.[23] Figure 2 below shows these potential savings. Table II presents these as both a per-antenna savings (as found in Figure 1 above) and a total projected savings for the ten year forecast (as found in Figure 2 below). When we account for the number of expected antenna reflectors needed over the next decade, it becomes clear that a facility which services GEO satellites would be most worthwhile. It is estimated that an ISM provider could spend approximately $3.5B on developing and deploying an ISM facility to GEO and breakeven by capturing the entire forecasted market. Clearly, capturing the entire forecasted market is not reasonable, but this value does give an upper absolute bound on how much should be spent on such an ISM facility.

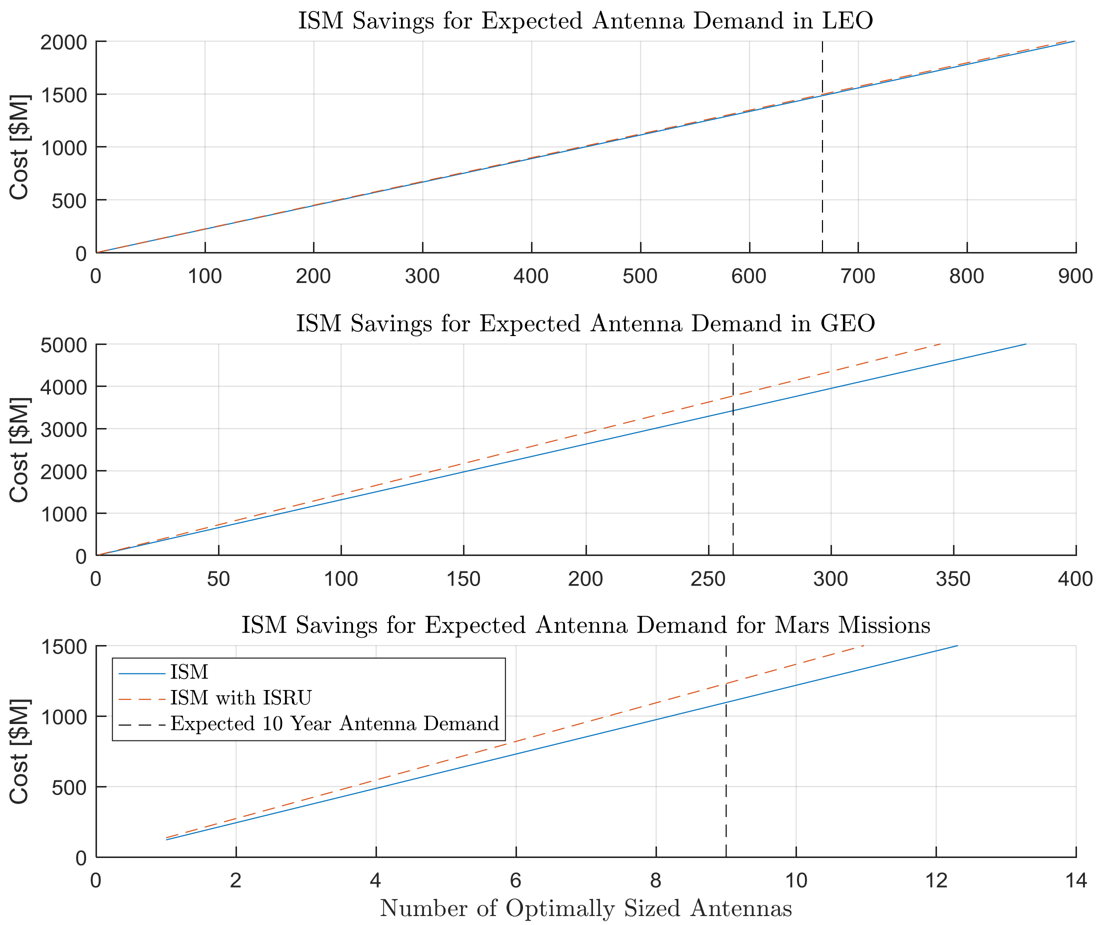


**Figure 2. Potential savings by implementation of ISM of antenna reflectors, by amount produced.**

**Table II. Summary of approximate potential savings by implementation of ISM of antenna reflectors, both per-antenna and total over 10 years.**

| | ISM | | ISM-ISRU | |
|---|---|---|---|---|
| | Savings per Antenna ($M) | Estimated Ten Year Savings ($M) | Savings per Antenna ($M) | Estimated Ten Year Savings ($M) |
| LEO | 2 | 1500 | 2 | 1500 |
| GEO | 13 | 3500 | 15 | 3800 |
| Mars | 120 | 960 | 140 | 1300 |

This analysis ignores some effects of producing antennas in-situ with ISM. Large, multi-meter-diameter antennas may impact attitude determination and control system requirements due to changes in necessary pointing accuracy, mass properties, and structural dynamics. It was also assumed that antennas could be made in space which are equal in performance to more traditional systems including antenna efficiency and antenna areal density. It may or may not be possible to achieve this depending on choice of ISM materials, processes, and fabrication quality and reliability. Lastly, the total savings over Earth launch estimates assume that all antennas are optimally sized to the diameters given in Figure 1 which does not account for some communications requirements for pointing and gain and other higher order system requirements.

Overall, the results show that ISM can be valuable for antenna reflector production. The GEO satellite market provides the best opportunity for industry savings and could also prove to be a business opportunity for an ISM facility operator. Future work will investigate facility designs and their costs including development of new technologies, deployment, and operations to determine feasibility of meeting break-even costs found in this analysis.

## V. Case Study 2: Solar Panel Manufacture

Nearly all spacecraft rely on photovoltaic solar arrays to generate power in orbit [24]. Over the years, power generation has increased due to improved solar cell efficiencies and an evolution from body-mounted solar panels to rigid and flexible deployables.[25] In addition to total power, solar arrays are evaluated on performance metrics including specific power (W/kg), stowed volume efficiency (kW/m$^3$), and specific cost ($/W). Solar arrays are constrained by required stiffness, or fundamental frequency, and strength, which is based on launch and operational loading. Solar arrays also need to reliably provide power over the life of the spacecraft.

There is significant interest in improving solar array performance by designing arrays that are cheaper, lighter, more compactly stowed, and generate more power. Existing arrays typically produce 10-20 kW at 60-178 W/kg and 10-40 kW/m$^3$ with a cost of $1,000/W.[26] For Mars missions and beyond, NASA has expressed a need for solar arrays that can generate >100 kW at >150-300 W/kg and >60 kW/m$^3$ with a cost of $250/W.[24,26,27] Increased specific power is particularly important for increasing the acceleration achievable by electric propulsion systems. Hoping to achieve these goals, NASA has funded development of advanced solar array systems such as the Orbital ATK Space Systems MegaFlex and the Deployable Space Systems Mega-ROSA, a smaller version of which was deployed on ISS for testing in June 2017. [28,29]

ISM appears to be another promising way to produce solar arrays with improved performance.[4,13] Without launch fairing constraints, very large ISM arrays can be produced to meet increased power demand. ISM arrays can improve stowed volume efficiency because raw material for construction is much more compact than existing deployables. ISM arrays can increase specific power by reducing solar array mass through structural optimization for microgravity in-space loads and the elimination of deployment mechanisms. Historically, solar array reliability has been a major problem, with failures accounting for about half the total cost of spacecraft insurance claims.[30,31] The average solar array anomaly insurance claim has been about $100M, and failures often occur in the first year of operation.[30] ISM could improve reliability by allowing for repair, replacement, and upgrades of arrays over time while eliminating the risk of deployment failures.[31] In addition, a spacecraft could be designed with the intent to nominally receive ISM solar arrays to take advantage of the aforementioned benefits.

Various proposals for ISM of solar panels exist, such as Tethers Unlimited's SpiderFab and Made In Space's Archinaut.[9,32] Tethers Unlimited, Inc., (TUI) envisions using its SpiderFab architecture to produce extremely large, lightweight solar arrays. TUI has demonstrated proof-of-concept by fabricating a truss structure for deployment of an emulated thin-film solar array blanket using its Trusselator element.[33] TUI envisions a 300 kW array would achieve up to an order of magnitude reduction in structural mass fraction due to the increased specific bending stiffness of its in-space manufactured trusses compared to existing deployables.[33]

This case study analyzes the cost and benefit of ISM solar panels to determine the conditions under which it is commercially viable to produce ISM arrays. This analysis assumes that some free-flying ISM facility exists which uses raw material stock to produce solar panel structural support. In this scenario, solar cells are launched as a compact, folded flexible array blanket which is stretched over the ISM support structure in-space. The facility produces ISM arrays that generate the same total power and meet the same fundamental frequency constraints as Earth-launched arrays. However, the arrays can still differ in mass, stowed volume, and cost. An ISM array is deemed commercially viable for power levels at which it is cheaper than the current launched array option. However, ISM arrays can also provide additional benefit through improved performance. The process of delivering and integrating the solar array with a customer spacecraft is not explicitly considered in this analysis. Assuming operations in GEO, the phasing maneuver to deliver the solar array would have a small propellant requirement.

The analysis begins by determining solar array cost as a function of power generated. The total cost is the sum of the following cost contributions: launch cost of the total solar array mass, the material cost of the structure, the cost of the solar cells, and the cost of the ISM facility. The cost of conventional launched arrays serves as the baseline. The cost is estimated for notional ISM arrays that have been structurally optimized for in-space loads. Figure 3 below shows the high-level methodology used to compute solar array system cost.

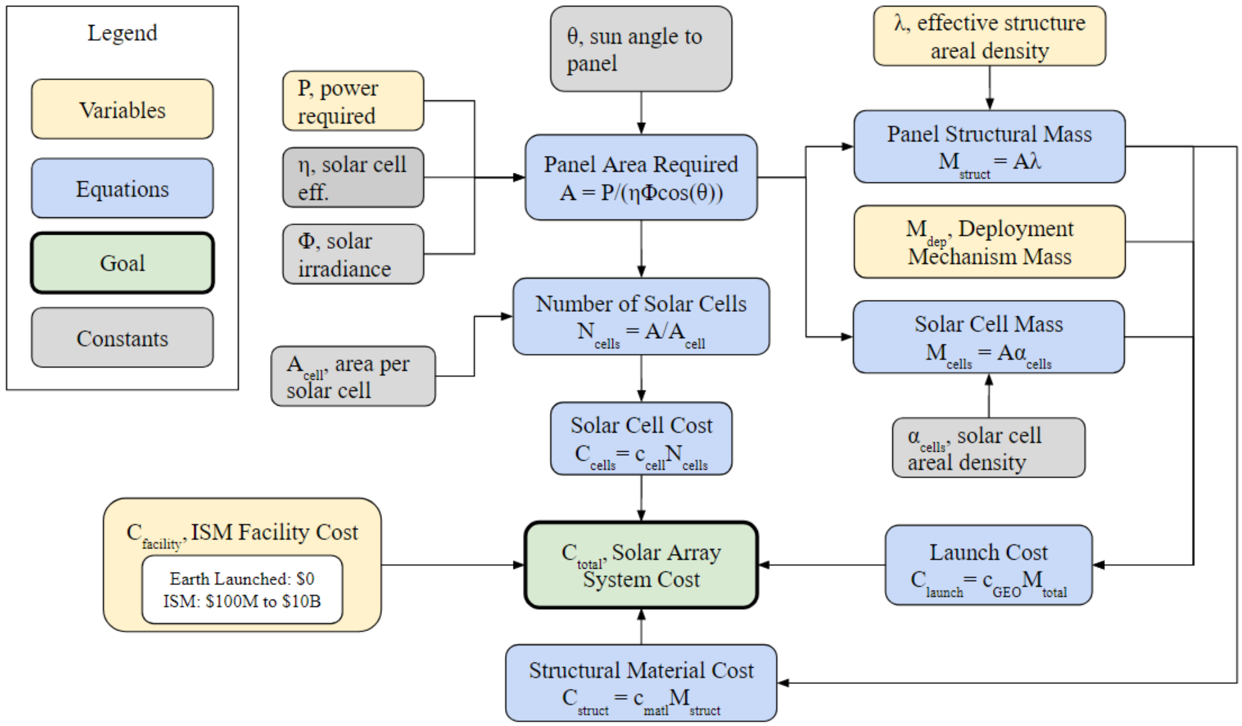


**Figure 3. Process flow for determining solar array system cost as a function of launch, material, solar cell and ISM costs.**

The launch, material, and solar cell cost are each modeled as linearly proportional to the total array mass, structural mass, and number of solar cells, respectively. Facility cost was allowed to vary between $100M and $10B to capture reasonable expectations for that uncertain cost and to allow sensitivity analyses to be performed. The cost was broken down into the above contributions to facilitate comparison between launched and ISM arrays by adjusting the factors in the cost contributions for each case. The differences between the two cases arise in the areal density of the structure, the deployment mechanism mass, and the facility cost. The mass and cost for the baseline case was validated with existing solar array cost models and performance metrics.[18] However, the most important aspect is the relative cost between launched and ISM arrays. The resulting expression for total cost, $C_{total}$, as a function of array area, A, is shown below:

$$C_{total} = C_{facility} + c_{GEO}M_{dep} + A\left[\frac{c_{cell}}{A_{cell}} + c_{GEO}\alpha_{cells} + (c_{matl} + c_{GEO})(\lambda)\right] \tag{1}$$

where $\lambda = \frac{\omega\alpha}{\epsilon}$ is an effective areal density, and $P = \eta\phi\cos(\theta)A$ relates power generation to array area. The above equation for cost as a function of array area, which is related to power by incident solar flux and solar cell efficiency, is plotted in Figure 4 assuming a facility cost of $100M and an ISM array structure with 20% of the structural mass of a typical launched rigid deployable array, which has a specific power of ~60 W/kg. The complete set of inputs used are given in Table IV in the appendix.

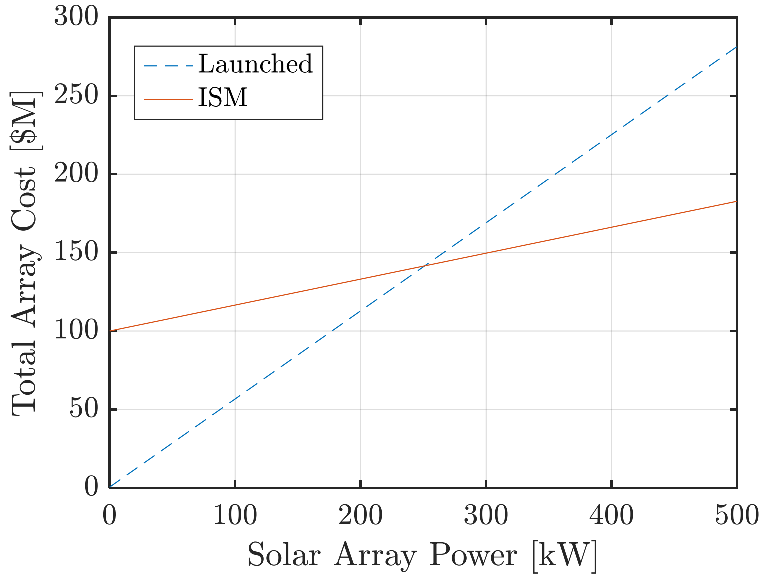


**Figure 4. Cost vs. power generation for both launched and ISM solar arrays.**

Figure 4 above shows that ISM arrays have a large fixed cost due to the cost of the ISM facility. However, ISM arrays have a smaller incremental cost than launched arrays as power level is increased. This is due to the reduced mass of the array achieved by structural optimization for in-space loads instead of launch loads. This lower mass leads to a reduced launch cost and material cost. In this case, the breakeven point occurs at 250 kW of total power. To be cost competitive with existing arrays, the free-flying ISM facility must produce a total of 250 kW of power, which could be distributed among multiple customer spacecraft as separate sets of arrays. If the breakeven power is less than the total power required for a single spacecraft, then that mission could justify using a dedicated ISM facility.

Facility cost and structural mass savings for an ISM array are highly uncertain at this point in the development of ISM technology. Thus, it is beneficial to determine the sensitivity of the breakeven point to these factors. This analysis will provide insights into the technology development effort, in terms of facility cost and structural optimization, needed to make ISM solar arrays commercially viable. Structural optimization for an ISM solar array was not conducted in this analysis, but would be based on in-orbit loads, such as thermal snap, plume impingement, thruster acceleration, and slewing, as well as vibrations and fundamental frequency constraints. The facility cost would depend on the particular ISM technology used and its development process.

The array area at which the cost of an ISM solar array breaks even with a launched array, as seen in Figure 4, can be found analytically using equation 1. That expression can be rearranged to find the maximum allowable facility cost, $C_{facility,max}$ , as a function of the desired breakeven array area, $A_{BE}$, for a given structural mass fraction, $\nu = \alpha_{ISM}/\alpha_{launch}$ and a deployment mechanism mass fraction, $\mu = M_{dep,ISM}/M_{dep,launch}$. The equation is given below and then plotted in Figure 5 below:

$$C_{facility,max} = A_{BE}(c_{matl} + c_{GEO})\lambda_{launch}(1-\nu) - c_{GEO}M_{dep,launch}(\mu - 1) \tag{2}$$

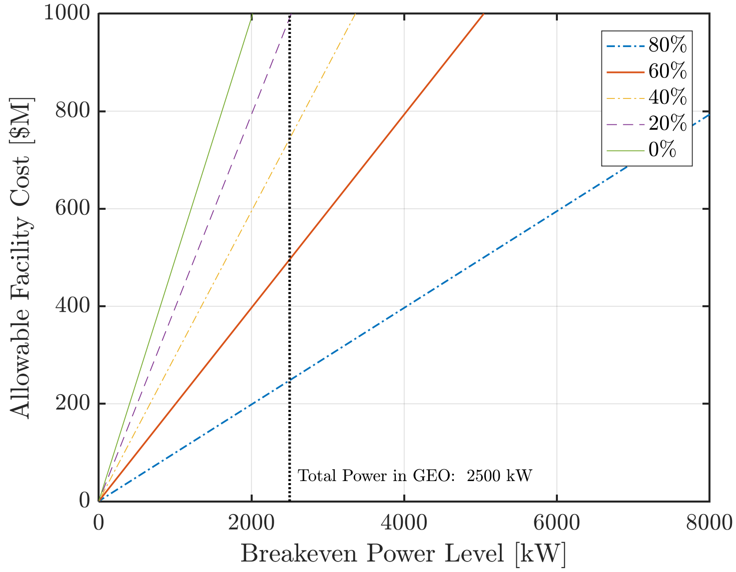


**Figure 5. Allowable ISM facility cost as a function of breakeven power generation for several values of structural mass fraction. For example, the purple, dashed curve indicates an ISM array with 20% of the structural mass of a typical launched rigid deployable array.**

Figure 5 shows that for a given desired breakeven solar array production and expected structural mass fraction, the maximum allowable facility cost for commercial viability can be determined. The figure allows evaluation of proposed ISM facility costs to ensure commercial viability for solar array production. Assuming there is an inverse relationship between actual facility cost and structural mass fraction achievable, this figure would guide selection of the facility design that minimizes the breakeven power production. The total power across all spacecraft currently in GEO would be a theoretical maximum limit on breakeven power, which would represent capturing the entire current GEO market for solar arrays. A theoretical case with zero structural mass is shown as a limiting case. Note that there are diminishing returns on allowable facility cost as structural mass fraction is reduced. Interestingly, higher specific launch costs make ISM more favorable because the cost savings for ISM arrays arise from reduced structural mass. This is shown in equation 2, where the partial derivative of allowable facility cost with respect to specific launch cost is positive. Thus, falling launch costs can threaten the ability of mass-saving ISM applications to compete on cost. This result also shows that ISM proves most beneficial for use far from a gravity well, where mass is at a premium.

The structural mass fraction not only impacts commercial viability through breakeven power, but also through improvement of solar array performance. If mass is reduced for a given power array, the specific power increases. This reduced mass also leads to reduced cost in launch and materials, which reduces specific cost. Additionally, the mass required is launched as compact raw material, which increases stowed volume efficiency. The impact of structural mass fraction on these performance metrics is shown in Figure 6. It shows that desired improvements in the state-of-the-art for solar panels can be achieved provided a sufficient structural mass fraction is achieved. The 100% mass fraction data point represents a conventional rigid array with 70 W/kg. At 0% mass fraction, the performance is limited by the cost and mass of solar cells. An 11% mass fraction meets the far-term vision of 300 W/kg performance.[24]

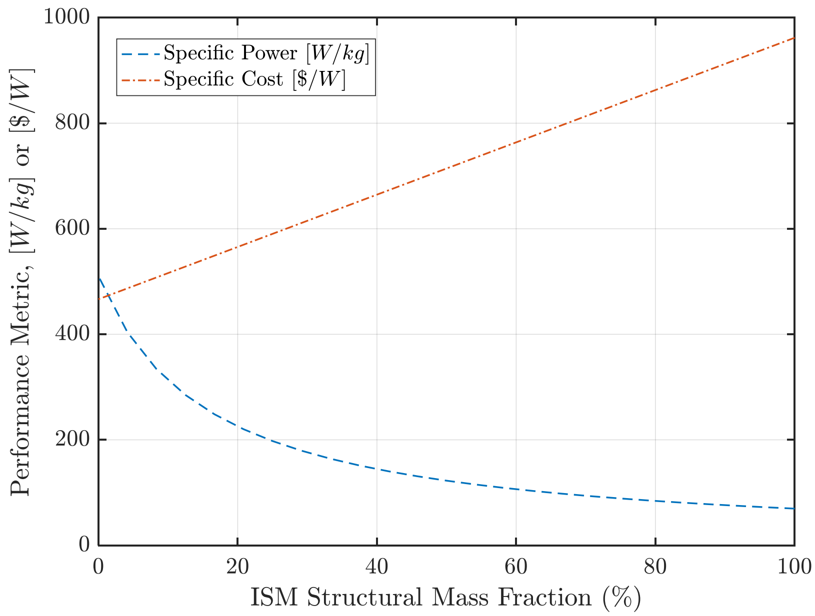


**Figure 6. Specific power and specific cost vs. structural mass fraction for a 10 kW array produced by a $100M facility capable of producing a total of 250 kW.**

## VI. Case Study 3: Spare Parts Manufacturing

One of the major challenges associated with long-duration human spaceflight operations, including LEO space stations such as the ISS, is the provision of spare parts to maintain system operations. Due to the stochastic nature of maintenance demands, spare parts manifesting is a balance between risk and resources. When spare parts are provided as discrete, prefabricated items – as is traditionally done – a significant amount of mass is required to provide a high level of risk coverage. A large portion (approximately 95%, in some cases) of the spare parts provided will not be used, but they are still required for risk mitigation since it is impossible to know beforehand *which* spares will be used.[15] As a result, traditional spare parts are a relatively inefficient way to fulfill maintenance demands. ISM could be applied to reduce the amount of mass required for maintenance by enabling the production of spare parts on demand using common raw materials. Previous studies have shown that the application of ISM to crewed Mars missions could significantly reduce logistics mass.[14,16,17] For future commercial LEO space stations, ISM could be applied to reduce logistics resupply costs.

The third case study investigates the application of ISM for the creation of spare parts on demand using common raw materials. Specifically, this analysis examines maintenance logistics mass associated with Environmental Control and Life Support (ECLS) equipment for a notional Earth-orbiting commercial space station which is resupplied every 90 days. Two cases are examined. In the first, spare parts are provided in the traditional way (i.e. manufactured on Earth and launched on resupply flights). For the second, a notional ISM capability is used to manufacture spare parts for a subset of items on-demand when failures occur, using raw material feedstock launched from Earth. In each case, the minimum total mass of spare parts and feedstock required to maintain a desired Probability of Sufficiency (POS) – defined as the probability that sufficient resources are provided to cover all failures that occur during the mission – is calculated. The general supportability and ISM analysis methodology used here is described in greater detail by Owens et al.[14] and Owens and de Weck[16], and the spares campaign analysis technique is described by Do et al.[34] and Do et al.[35] However, for simplicity this particular case study does not include the effects of epistemic uncertainty in item failure rates.

For the cases with and without ISM capability, the total mass of spares and feedstock required for a sequence of 10 resupply missions, occurring at 90-day intervals, is examined across a range of POS levels from 0.99 to 0.9999. The launch cost associated with maintenance logistics mass is then estimated using a specific launch cost to LEO of $2,700/kg.[19] A series of 10 resupply missions is examined, corresponding to approximately two and a half years of station operations. The difference between the launch cost in the case with no ISM and the case with ISM yields the launch cost savings that could be achieved with the notional ISM capability examined here. The results of this analysis are shown in Figure 7.

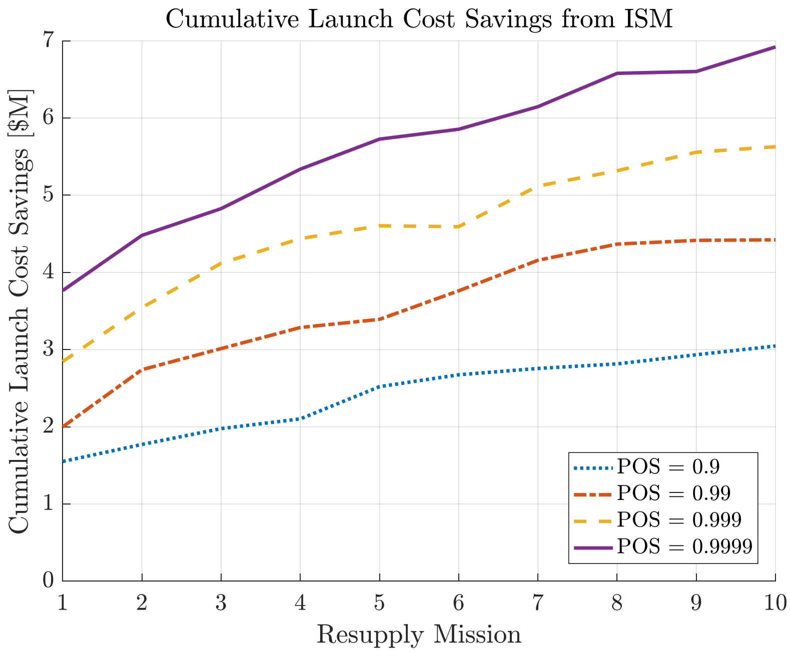


**Figure 7. Cumulative launch cost savings resulting from the application of ISM for the production of spare parts on demand for a notional commercial LEO space station, resupplied at 90-day intervals**

These results indicate that ISM does have the potential to reduce the cost of resupply for a commercial station, even looking specifically at spare parts associated specifically with a single subsystem. The launch cost savings increase as higher risk requirements are levied on the system (i.e. higher POS levels). Most of the savings occur in the first mission, when the on-orbit spares allocation must be initialized. In subsequent missions, the spares supply need only be replenished to account for failures that have occurred in the time since the last resupply mission, and as a result the resupply cost is generally lower in both cases. However, in either case ISM enables a reduction in logistics mass, and therefore launch costs, associated with maintaining a space station.

For the purposes of this analysis the assumed ISM capability – in terms of which components can be manufactured on-demand using ISM – is notional and is not meant to indicate that such a capability currently exists. Instead, this analysis assesses the potential value of such a capability if it were to be developed and implemented. Specifically, approximately one third of items are assumed to be manufacturable. The value of a particular manufacturing capability depends on the number of items in the system that can be manufactured, as well as which particular items are manufacturable, and these variables should be investigated in greater depth in collaboration with ISM technology and system design experts.

## VI. Discussion

The business cases for the ISM facilities in the antenna and solar array case studies were developed with one major assumption: that they only produced one type of component, namely the one being considered in each case study. In reality, one would expect a free-flying ISM facility to be capable of constructing components of many different types and even materials. Thus the conclusions drawn from these case studies can be taken as rather conservative – an ISM facility capable of making multiple components would have, at least at a first-order, higher returns. Regardless, these facilities would need to become a reality in order for ISM to be possible for most satellite-servicing applications.

The promise of the commercial applications of ISM investigated here can lead to strategic paths for technology development and maturation by both government and private sector groups. NASA and various government and industry partners can work to mature technologies in the fields of autonomous robotics, in-situ recycling, ISRU, precision guidance and control, and space-based manufacturing techniques such as microgravity metal 3D printing and subtractive methods. Apart from being key enablers of ISM, they also form the network of capabilities necessary for extending humanity's reach beyond LEO permanently. As discussed in Section II, many of these technologies are already being developed and tested; further work and more research and demonstration missions are needed. Most importantly, NASA and its partners must plan for the evolving needs and solutions of the emerging space industry.

Such analysis could even reveal competition to the ISM paradigm, including potentially drastically reduced launch costs in coming years. The uncertainty inherent in such a fluid and active market requires continual re-evaluation of state of the industry as it relates to ISM.

While industry-wide considerations are important, further work could also be done for specific ISM applications. This could include analyses with more breadth – investigating the impact of ISM of one component or subsystem on the design of the entire spacecraft or system. This could also capture testing, validation and verification of parts without the necessary physical access to the part as is needed on Earth. In the antenna case study, we investigate the combined effect on power and communications subsystems; one could expand that analysis for other areas such as payload capabilities, data handling, attitude control, and antenna qualification. Another type of analysis could capture more depth – investigating higher order technical effects that could arise from building components outside of the traditional Earth-based methods.  These could all yield more insight into the proper business, programmatic and technical conditions which lead to successful ISM deployment.

## VII. Conclusion

This work analyzed three case studies where ISM may prove to be a viable commercial option. The antenna reflector study found that the most promising regime for ISM to take hold is for GEO communications satellites, as there is a significant future market for satellites to that destination and because delivery of Earth-launched systems is already so expensive. The solar panel study emphasized key power generation characteristics that drive the value of ISM over launch. It found that the more ISM could leverage the absence of substantial launch loads via improved mass fractions, the more powerful the ISM effect can be. Lastly, the spares logistics analysis found that ISM businesses could reduce operations costs for Earth-orbiting commercial space stations. Recommendations were made to NASA to continue its thrusts in maturing technologies related to ISM and to develop a strategic roadmap for its support for the innovative potential of commercial space. This would prove beneficial to both the future of commercial space and to NASA’s own long-term goals. Future work includes analyses with greater breadth and depth, and perhaps preliminary design of a reference free-flying ISM facility.

## Acknowledgments

This research was supported by a research grant from the NASA Emerging Space Office (proposal number 15-ESO-0002), as well as NASA Space Technology Research Fellowships (grant numbers NNX14AM42H and NNX16AM76H). The authors would like to thank Dr. David Miller and Dr. Afreen Siddiqi for their insights and guidance throughout the project.

## Appendix

**Table III. Parameters and Assumptions for the antenna reflector case study**

| | LEO | GEO | Mars |
|---|---|---|---|
| Data rate (Mbps) | 100 | 100 | 2* |
| Frequency (GHz) | 11.7 | 11.7 | 8‡ |
| Antenna Efficiency | 0.55 | 0.55 | 0.55 |
| Non Comms. Power (W) | 500 | 500 | 500 |
| Encoding | BPSK | BPSK | BPSK |
| Receiver Gain (dB) | 40 | 40 | 77.2† |
| Noise Temp (K) | 135 | 135 | 37.75† |
| Bandwidth (MHz) | 500 | 500 | 5.5* |
| Antenna Areal Density (kg/m2) | 1.6552 [18] | 1.6552 [18] | 1.6552 [18] |
| Specific Launch Cost ($/kg) | 2700 [19] | 8300 [19] | 15500 [19] |

* - based on values obtained for the Mars Reconnaissance Orbiter mission
† - based on values obtained for the NASA’s Deep Space Network
‡ - assumed to use X-band communications prevalent among deep-space missions.

**Table IV. Parameters and Assumptions for the solar array case study**

| Parameter | Symbol | Value |
|---|---|---|
| Solar cell efficiency | $\eta$ | 0.25 |
| Solar irradiance | $\phi$ | 1367 W/m$^2$ |
| Solar angle | $\theta$ | 0 deg |
| Deployment mechanism mass | $M_{dep,launch}$ | 20 kg |
| | $M_{dep,ISM}$ | 0 kg |
| ISM facility cost | $C_{facility,launch}$ | $0 |
| | $C_{facility,ISM}$ | $100M |
| Launch cost per kg to GEO | $c_{GEO}$ | $25,000/kg |
| Solar cell unit cost | $c_{cell}$ | $50/cell |
| Material cost per kg | $c_{matl}$ | $15,000/kg |
| Area per solar cell | $A_{cell}$ | 84 cm$^2$ |
| Ratio of boom to panel width for flexible arrays | $\omega$ | 1 |
| Solar cell areal density | $\alpha_{cells}$ | 0.67 kg/m$^2$ |
| Areal density of structural support | $\alpha_{launch}$ | 3.81 kg/m$^2$ |
| | $\alpha_{ISM}$ | 0.762 kg/m$^2$ |
| Solar cell packing efficiency | $\epsilon$ | 0.90 |

## References


[1] NASA, *NASA's Journey to Mars, Pioneering Next Steps in Space Exploration*, 2015.

[2] Dunn, J. J., Hutchison, D. N., Kemmer, A. M., Ellsworth, A. Z., Snyder, M., White, W. B., and Blair, B. R., "3D Printing in Space : Enabling New Markets and Accelerating the Growth of Orbital Infrastructure," *Space Manufacturing 14: Critical Technologies for Space Settlement*, 2010, pp. 29–31.

[3] Prater, T. J., Bean, Q. A., Beshears, T. D., Rolin, T. D., Werkheiser, N. J., Ordonez, E. A., Ryan, R. M., and Ledbetter III, F. E., "Summary Report on Phase I Results from the 3D Printing in Zero-G Technology Demonstration Mission, Volume I (NASA/TP-2016-219101)," 2016.

[4] Skomorohov, R., Welch, C., and Hein, A. M., "In-orbit Spacecraft Manufacturing : Near-Term Business Cases," *International Space University*, 2016.

[5] Jackson, B., "Made In Space celebrates a stellar year of 3D printing on the International Space Station" Available: https://3dprintingindustry.com/news/made-space-celebrates-stellar-year-3d-printing-international-space-station-109997/.

[6] Aron, J., "Print your own satellite – in space," *New Scientist* Available: http://linkinghub.elsevier.com/retrieve/pii/S0262407915310071.

[7] Hoyt, R. P., Cushing, J. I., Slostad, J. T., Jimmerson, G., Moser, T., Kirkos, G., Jaster, M. L., and Voronka, N. R., "SpiderFab: An architecture for self-fabricating space systems," *AIAA SPACE 2013 Conference and Exposition*, 2013, pp. 1–17.

[8] Hoyt, R. P., Slosad, J. T., Moser, T. J., Cushing, J. I., Jimmerson, G. J., Muhlbauer, R. L., Conley, A. J., Alvarado, S. R., and Dyer, R., "In-Space Manufacturing of Constructable ™ Long-Baseline Sensors using the Trusselator ™ Technology," *AIAA SPACE 2016 Conference & Exposition*, 2016, pp. 1–9.

[9] MadeInSpace, "Archinaut" Available: http://www.madeinspace.us/projects/archinaut/.

[10] DARPA, "Program Aims to Facilitate Robotic Servicing of Geosynchronous Satellites" Available: https://www.darpa.mil/news-events/2016-03- 25 DARPA.

[11] NASA, "Restore-L Robotic Servicing Mission" Available: https://sspd.gsfc.nasa.gov/restore-l.html.

[12] Owens, A. C., and de Weck, O. L., "Systems Analysis of In-Space Manufacturing Applications for the International Space Station and the Evolvable Mars Campaign," *AIAA SPACE 2016 Conference & Exposition*, Long Beach, CA: American Institute of Aeronautics and Astronautics, 2016.

[13] National Research Council, *3D Printing in Space*, Washington, D.C.: National Academies Press, 2014.

[14] Owens, A., Do, S., Kurtz, A., and de Weck, O., "Benefits of Additive Manufacturing for Human Exploration of Mars," *45th International Conference on Environmental Systems*, Bellevue, WA: International Conference on Environmental Systems, 2015.

[15] Cirillo, W., Aaseng, G., Goodliff, K., Stromgren, C., and Maxwell, A., "Supportability for Beyond Low Earth Orbit Missions," *AIAA SPACE 2011 Conference & Exposition*, Long Beach, CA: American Institute of Aeronautics and Astronautics, 2011, pp. 1–12.

[16] Owens, A. C., and de Weck, O. L., "Systems Analysis of In-Space Manufacturing for the International Space Station and the Evolvable Mars Campaign," *AIAA SPACE 2016 Conference & Exposition*, American Institute of Aeronautics and Astronautics, 2016, pp. 1–17.

[17] Wald, S. I., "Advanced Habitation Strategies for Aggressive Mass Reduction," *AIAA SPACE 2015 Conference and Exposition*, Pasadena, CA: American Institute of Aeronautics and Astronautics, 2015.

[18] Wertz, J. R., Everett, D. F., and Puschell, J. J., *Space mission engineering: the new SMAD*, Microcosm Press, 2011.

[19] SpaceX, "SpaceX Capabilities and Services" Available: http://www.spacex.com/about/capabilities.

[20] Cesaretti, G., Dini, E., De Kestelier, X., Colla, V., and Pambaguian, L., "Building components for an outpost on the Lunar soil by means of a novel 3D printing technology," *Acta Astronautica*, vol. 93, 2014, pp. 430–450.

[21] United Launch Alliance, "Delta IV Product Sheet" Available: http://www.ulalaunch.com/products_deltaiv.aspx.

[22] Northrup Grumman, "AstroMesh" Available: http://www.northropgrumman.com/BusinessVentures/AstroAerospace/Products/Pages/AstroMesh.aspx.

[23] Federal Aviation Administration, "2015 Commercial Space Transportation Forecasts," 2015.

[24] Beauchamp, P., Ewell, R., Brandon, E., and Surampudi, R., "Solar Power and Energy Storage for Planetary Missions," *Jet Propulsion Laboratory and California Institute of Technology* Available: http://www.lpi.usra.edu/opag/meetings/aug2015/presentations/day-2/11_beauchamp.pdf.

[25] Jones, P. A., and Spence, B. R., "Spacecraft Solar Array Technology Trends," *IEEE Aerospace and Electronic Systems Magazine*, vol. 26, 2011, pp. 17–28.

[26] NASA, "NASA Technology Roadmaps, TA 3: Space Power and Energy Storage," 2015, p. 2015.

[27] Piszczor, M., Briggs, M., and Mason, L., "STMD Power & Energy Storage," *NASA SBIR Workshop*, 2016.

[28] NASA, "NASA Seeks Game Changing Solar Array Systems Proposals" Available: https://www.nasa.gov/home/hqnews/2012/apr/HQ_12-132_Solar_Array_Proposal.html.

[29] NASA, "Advanced Solar Array Systems" Available: https://www.nasa.gov/offices/oct/home/feature_sas.html.

[30] Frost & Sullivan, "Commercial Communications Satellite Bus Reliability Analysis," 2004.

[31] Ellery, A., Kreisel, J., and Sommer, B., "The case for robotic on-orbit servicing of spacecraft: Spacecraft reliability is a myth," *Acta Astronautica*, vol. 63, 2008, pp. 632–648.

[32] Hoyt, R. P., Cushing, J. I., Slostad, J. T., Jimmerson, G., Moser, T., Kirkos, G., Jaster, M. L., and Voronka, N. R., "SpiderFab: An architecture for self-fabricating space systems," *AIAA SPACE 2013 Conference and Exposition*, American

Institute of Aeronautics and Astronautics, 2013, pp. 1–17.
[33] Hoyt, R., "TRUSSELATOR - On-Orbit Fabrication of High Performance Support Structures for Solar Arrays, Phase I," *NASA Space Technology Mission Directorate, SBIR/STTR Programs*.
[34] Do, S., Owens, A. C., and de Weck, O. L., "HabNet - An Integrated Habitation and Supportability Architecting and Analysis Tool (submitted for publication)," *45th International Conference on Environmental Systems*, 2015.
[35] Do, S., Owens, A., Ho, K., Schreiner, S., and De Weck, O., "An independent assessment of the technical feasibility of the Mars One mission plan - Updated analysis," *Acta Astronautica*, vol. 120, 2016, pp. 192–228.