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Made In Space, Expectations Management, and the Business of In-Space Manufacturing

On April 11, 1970, just two days into NASA's Apollo 13 mission but already 200,000 miles above Earth, an onboard oxygen tank exploded, leaving astronauts James Lovell, John Swigert, and Fred Haise to watch helplessly as their precious oxygen supply leaked out into space. Over the next three days, as a cascading set of failures to other critical on-board systetrms took hold, the crew was in constant contact with NASA's Mission Control in Houston, seeking a safe return to Earth.

A critical problem was that the spacecraft's carbon dioxide removal system had been designed to support two men for two days, but it would now have to care for three men for four days. Frustratingly, enough lithium hydroxide canisters – which removed carbon dioxide from the spacecraft – were on-board, but the square canisters were incompatible with the round openings in the lunar module's environmental system. As Lovell later recalled, "we [were dying] of the exhaust from our own lungs."[1]

In Houston, Texas, the engineers at NASA Mission Control devised a contraption to join the mismatched parts of the carbon dioxide removal system. According to Lovell, "they had thought up a way to attach a CM canister to the LM system by using plastic bags, cardboard, and tape – all materials we had on board." From Houston, CapCom Joe Kerwin led Swigert step-by-step for an hour through the steps required to recreate the contraption designed on Earth. Later, when he saw the prototype on Earth, Lovell remarked, "it looks just like the one we made."[2]

The risks revealed by the Apollo 13 mission worsened over the next several decades of space activity, as crewed missions—especially those on the International Space Station (ISS)—grew longer and more complex. Inevitable mistakes and failures in equipment could be life-threatening for astronauts with access to only the limited supplies that could be brought onboard, and anticipating all possible needs before flight was an impossible task.

In response to these risks, space programs were forced to send large supplies of backup tools and equipment onboard spacecraft and to the ISS, a costly and imperfect solution given the expense of launch and the difficulty of anticipating specific failures. These inefficiencies also discouraged more ambitious space missions, where the risks posed by equipment failure would have been still greater.

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Meanwhile, innovations in three-dimensional (3D) printing raised the tantalizing possibility of mitigating these risks and thereby dramatically facilitating expanded human activities in space. The earliest 3D printers were conceived in the late 1980s, when they were called Rapid Prototyping (RP) technologies.[3] Three decades later, costs of 3D printing had fallen dramatically, and a host of companies brought 3D printing into the mainstream. The technology was heralded by some as signaling the start of the 4th Industrial Revolution, with anticipated far-reaching effects on the industrial sector."[4]

A turning point in the idea of using 3D printing to manufacturing needed objects *in space,* and thus move beyond stockpiled spare parts and jerry-rigged solutions, took place at Singularity University (SU) in 2009. SU had been founded just a year earlier by space entrepreneur Peter Diamandis and futurist Ray Kurzweil to "nurture advancing technologies that [would] move humanity toward the technology singularity". Its Graduate Studies Program, hosted at the NASA Research Park in Silicon Valley, was a 10-week intensive session designed to teach students "[to] learn to read the news differently and identify which of all the crazy breakthroughs might be relevant…[giving] people hope for the future and a credible path for getting there."[5]

One of SU's professors was three-time shuttle astronaut Dan Barry, who was intrigued by the possibility of printing in space and shared this vision with three students: Aaron Kemmer, Jason Dunn, and Mike Chen. As Barry remarked, "having a 3D printer on the ISS would sure be useful,"[6] a sentiment later elaborated upon by Jason Crusan, director of NASA's Advanced Exploration Systems: "even with our cargo flights today, the space in between cargo flights [to the ISS] is three to four months at least, so our ability to be responsive there is still on the order of months, and [a] 3D printer could be responsive in the order of hours."[7]

The three SU students and final co-founder, Michael Snyder (who consulted with the team while finishing graduate studies at the Ohio State University), embraced Barry's vision and founded a company—Made In Space—with the goal of putting a 3D printer on the ISS, enabling astronauts to print a wide range of useful objects on demand.

From these humble beginnings, Made In Space (MIS) would spend its early years establishing its reputation as a company of "firsts". MIS was the first to 3D print in space, the first to manufacture a tool in space, and the first to successfully address the problem of additive manufacturing in space.

Perhaps even more remarkable was the ability of MIS's leadership, in particular its CEO Andrew Rush, to set, manage, and reach expectations in such a challenging, risky, and dynamic sector as space manufacturing. Over the years, MIS was heralded by space enthusiasts as a leading example of the future of commercial space and a linchpin for humanity's expansion into space. Such an exalted position was no doubt precarious, but MIS had managed to avoid a fall from grace. Some attributed MIS's success to its disciplined use of both a stepwise, iterative approach to technology development (in close partnership with NASA) and its atypical funding model. Without taking dilutive venture capital, MIS instead pursued small business grants from NASA to fund research and development.

As MIS looked to the future, its CEO Andrew Rush gave careful thought to its strategy and its place in the broader space sector. After having proven its base technology (3D printing) through NASA solicitations and contracts, MIS was searching for a viable commercial application. But the business case for the leading candidate, high-quality fiber optic cable for use on Earth, remained uncertain. In 2019, MIS secured a major contract from NASA for early work on a much grander project, called Archinaut, to build architectures in space that would enable off-Earth habitation. Was that opportunity a more promising path for MIS, or did its ambition risk distracting MIS from its more managed, incremental strategy? Which strategy would enable MIS to retain its central place in facilitating the development of the space economy?

Additive Manufacturing in Space

A decade before Made In Space was founded, NASA had already made substantial investments in pursuing the promise of additive manufacturing technology. Additive manufacturing describes the process of joining materials to make objects, usually building layer upon layer of materials (as in 3D printing). In 1999, NASA researcher Ken Cooper became the first to demonstrate the viability of the technology in microgravity.[8]

NASA hoped that by maturing additive manufacturing technology, the agency could revolutionize the costs of human activity in space in two ways.

First, 3D printing would enable general and affordable in-space servicing and repair, capabilities that NASA's experience with the Hubble Space Telescope had demonstrated would be vital for extending and ensuring long-duration space activities. Hubble was the first major optical telescope to be placed in space, and, orbiting at 547 km, it was the first telescope to be designed for servicing missions by astronauts. Between 1993 and 2009, astronauts completed five in-space servicing missions, credited for extending the lifespan of the telescope well past the initial 15-year estimate. The first servicing mission corrected for a critical flaw in the primary mirror, and subsequent missions improved and added capabilities to the instrument.

Although falling short of true in-space manufacturing, this servicing mission proved the importance of accessing in-space assets once launched. When the successor to the Hubble Telescope, James Webb Space Telescope, was originally proposed, astronomers and engineers insisted that it too should be designed to be serviced. John Grunsfeld, former astronaut and Hubble Telescope servicer, remarked that with the ability for on-orbit servicing "you now have the equivalent of a ground-based observatory, that you can upgrade and change. It is now a facility rather than one you have to build, throw away, and build again."[9]

Second, and more subtly, 3D printing would free NASA and commercial space players from the "tyranny of launch"[10] that had meant space assets were "not built to maximize performance in the operational environment, but to survive the delivery mechanism… machines need to survive launch rather than operate in space."[11] In particular, the harsh launch environment required extra structural supports and electronic redundancies, while standardized deployers limited size, shape, and mass (See **Exhibit 1** for a comparison of launch loads and forces experienced in microgravity). In order to fit into the designated payload fairing of available orbital launch rockets, deployed objects had to be packed and folded, and then deployed once the fairing injected it into the desired orbit. The entire system was once described by NASA as "like origami".[12] The promise of additive manufacturing would be to introduce a new paradigm best summarized with the phrase: "make it, don't take it."[13]

The International Space Station provided a prominent example of both hopes for 3D printing. First, astronauts lived on-board for months at a time, but resupply missions operated only every couple of months. NASA's solution was to keep a stock—an estimated 13,170 kg—of spare parts on-board and another stock – some 17,990 kg – on Earth and perennially ready for launch. Based on historical data, it was estimated that 95% of those spares would never be used, since anticipating which spares would be needed was impossible.[14] Second, the construction of the ISS went far over the expected budgets for both time and funding, at least in part because it couldn't be manufactured in space. Instead, the ISS was sent into LEO through multiple launches and eventually assembled while in orbit. Launching the massive structure into space in separate parts raised engineering costs, dramatically constrained its design, and complicated its assembly and maintenance.

Made In Space: Act I

The founders of Made In Space (MIS), as co-founder Aaron Kemmer recalled, "were serial entrepreneurs hunting for a big idea. We wanted to start a company that would help open the space frontier. We were definitely not thinking the way forward was going to be 3D printing."[15]

MIS's focus on 3D printing arose from the observation that the ISS supply chain was, in the words of co-founder Dunn, "the longest, most complicated, and most expensive supply chain in existence." Based on a NASA study, the team estimated that 30% of the manifest parts on-board the ISS (parts which were paid for but not flown) were manufactured from plastic, meaning they could be made by a 3D printer. Based on that logic, if they could successfully demonstrate the use of 3D printing on-board the ISS, they could replace 30% of the parts. Ultimately, they hoped to go beyond plastics, printing mixed materials (which constituted 60% of parts on-board the ISS) and, eventually, electronics.

With a small amount of pre-seed funding from Singularity University's venture fund and permission to set up early operations on the NASA Ames campus, the co-founders got to work prototyping early models of the technology. Initially, they faced several novel engineering challenges in developing a 3D printer that would function on the ISS. First, in the absence of gravity, the prevailing force acting in the printer would be surface tension, complicating the basic mechanism for 3D printing. Second, the team hoped to place the printer in the ISS, meaning they would have to design additional safety modifications, especially since 3D printing emitted a toxic gas as a byproduct which could threaten crew safety in a closed environment.

After testing dozens of models in a series of parabolic flights through NASA's Flight Opportunities Program, the MIS founders decided to develop their own printer. According to co-founder Chen, "we found in that research that none of [the printers] were working. So we started tweaking them, hacking them, making a lot of changes, then doing more parabolic flight testing, and making more changes. Finally, we realized we had to make so many changes that it was much better to make our own design from scratch."[16] By 2011, based on results from the NASA Flight Opportunities testing, MIS was able to demonstrate additive manufacturing technology that could operate fully in microgravity.

MIS's relationship with NASA was solidified in 2012 when, following the success of its microgravity experiments, NASA awarded MIS its first Small Business Innovation Research (SBIR) Phase I grant. Congress established SBIR in 1982, requiring federal agencies with research and development (R&D) budgets greater than $100 million to offer grant opportunities that would encourage small businesses to commercialize innovations derived from federal R&D.[17] Within NASA, SBIR was implemented to "merge the overarching potential of small firms with the legendary intellect of NASA", and consisted of three phases. Phase I was idea generation, in which NASA granted $125,000 in funding over 6 months. During Phase II, prototype development, NASA distributed $750,000 over 24 months. The final phase, Phase III, was infusion or commercialization of the technology.[18] The three-phase, stepwise approach was specifically chosen to address the inherent technical and financial risk associated with bringing new products to the marketplace.

Beyond providing support to small businesses, NASA hoped to use SBIR to generate commercial demand for some of its assets, including the ISS. NASA had begun studying commercial use cases of the ISS in the 1990s, and since then it had brought commercial partners on board, for example deploying an external habitat module designed and manufactured by Bigelow Aerospace in 2016.[19] Increased commercial activities were intended to serve as an offset to ISS operations costs, with Robyn Gatens, deputy director of the ISS program stating, "we're hoping that new capabilities can develop that can one day take over for the space station, and we will begin to do that transition when those capabilities become available."[20] (See **Exhibit 2** for ISS operations costs compared to demand).

The Made In Space Additive Manufacturing Facility (AMF)

For the first SBIR Phase I contract, Made In Space proposed the development of an "Additive Manufacturing Facility" (AMF) on the ISS and described launching parts of a 3D printer to serve as "risk reduction" in planning for the ultimate installation of a fully-functioning 3D printer on-board. Moving on to Phase II allowed Made In Space to manufacture an engineering test unit based on the design conceived during Phase I.[21]

By 2014, Made In Space and NASA Marshall Space Flight Center built and flew a 3D printing module in Zero-G Experiment on the ISS, and in 2014, they remotely operated a 3D print payload for the first time (see **Exhibit 3** for a picture of the AMF and technical specifications). In 2014, astronaut and ISS commander Butch E. Wilmore became the first person ever to manufacture something in space. As MIS co-founder Jason Dunn said, "He needed a ratchet. We did it in five days. That went down as the fastest anything has ever gone from design concept to being in an astronaut's hand in space. Had Butch been on Mars, the story would have been almost identical."[22] By 2019, after three years in orbit, the AMF would be used to print hundreds of tools, charging customers for use of the facility (see **Exhibit 4** for an example of tools that could be printed using the AMF).[23] The company continued to receive SBIR funding, proposing the development of an in-space recycling system following the success of its experiments in 2014.[24]

Even in those early days, with just a single 3D printer in low-Earth orbit, the industry had high hopes for MIS. The picture of the first torque wrench made in space was shared throughout the media, heralded as symbolic of a new era in space manufacturing.[25] In total through 2017, NASA would invest $1.3 million in MIS through SBIR awards; by that time, the company had grown from three to 45 employees.[26]

Made In Space: Act II

MIS's early years had been a resounding success (see **Exhibit 5** for a timeline of major events), but when Andrew Rush was elevated from legal counsel to CEO in 2015, he realized that building on the company's reputation for "firsts" would require careful strategic thinking as well as continued operational excellence. Thus far, MIS had used its access to NASA funding and facilities to grow while keeping costs low and remaining relatively autonomous.

Unlike other space start-ups that pursued private financing opportunities, MIS would rely almost exclusively on NASA funding. As described by Rush, this decision came with important trade-offs. Working with NASA meant a slower development time; however, as a primary customer of MIS' early products, the company could cater solutions directly to the agency's needs. Not losing sight of critical commercial objectives, Rush stressed the importance of "staying focused on the vision and the frameworks to make the vision real" while collaborating with NASA.[27]

This early decision to partner with NASA would turn out to be helpful for both parties. The slow development period allowed the company ample time to reach important milestones and deliver proven technologies, all the while knowing that NASA would be a guaranteed first customer. For NASA, MIS became a poster child for the SBIR – it would continually use the company as a model for the efficacy of the program, including them in 2017 as an "SBIR/STTR Success Story".[28] In April 2020, Andrew Rush would be announced Chairman of NASA Advisory Council Regulatory and Policy Committee.[29]

Just as Made In Space found success through stable NASA funding, co-founders Mike Chen and Aaron Kemmer became involved with another tech start-up gaining traction. Overwhelmed, the co-founders brought Rush onboard to handle Made In Space operations as the new President, and eventual CEO in 2015. Kemmer would assume the Chairman position, with Michael Snyder acting as Chief Engineer, and Jason Dunn as Director.

Rush was a space enthusiast from his time completing an undergraduate degree in Physics. A patent lawyer by training, he joined Masten Space Systems' legal team upon graduation. Shortly afterwards, he became a partner at PCT Law Group, building a sustainable practice within a few years. He found his way to Made In Space, joining the team as general counsel, but often serving in an advisory role. When it came time for the co-founders to secure new leadership, Rush emerged as a clear choice.

While the transition was difficult early on, (as Rush commented, "NASA doesn't like change") he was able to secure some early wins, closing out a deal with Lowe's to partner on the first AMF to establish the "first hardware store in space."[30] This would be one of many strategic decisions made by Rush as the company grew from a small, Silicon Valley start-up into a space industry heavyweight headquartered in Jacksonville, Florida, near the Space Coast.

As MIS looked to the future, it faced the serious challenge of managing the high expectations that its success had generated and deciding whether to pursue commercial viability at a much greater scale. Rush and the MIS team considered two broad options for the company.

Exporting to Earth

According to co-founder Jason Dunn, "if we can grow industry in space, make things there and sell them on Earth…, what we start to do is build an economy that depends on activity going to and from space."[31] But achieving that vision would require identifying products with a specific—and perhaps rare—combination of characteristics. Alex MacDonald, senior economic adviser within NASA Headquarters' Office of the Administrator, pointed out that "you're still dealing with thousands of dollars per kilogram. So, whatever you are going to be making in space that you're going to be sending down to Earth has to be incredibly valuable but also available per unit of mass."[32]

The weakness of gravity off Earth had, since the early decades of the space age, prompted hopes that the in-space manufacturing of some goods might be uniquely cost-effective. In microgravity, materials did not separate by weight and could grow without encountering walls, allowing them to mix evenly and hold together without traditional supports. The ultrahigh vacuum of space also allowed for manufacturing without certain impurities.

Established in 2012, the Emerging Space Office (ESO) of NASA identified three cases in which technology development was impeded by problems caused by gravity: Silicon Carbide Wafers, Exotic Glasses and Fibers, and 3D Tissue Engineering (see **Exhibit 6** for a comparison of the technology readiness levels of these cases). These three case studies were identified due to their potential to foster innovation across many sectors, the relative advantage of producing them in microgravity, and the ease with which existing or slightly modified flight hardware could be used to produce them.

MIS undertook its own analysis, ultimately targeting a fiber-optic cable called ZBLAN (short for zirconium, barium, lanthanum, sodium, and aluminum), which offered a potential replacement for silica and other cables. Silica cables sold for as little as $20 per meter, while ZBLAN's market price was between $150 and $300 per meter for general use, and customized exotic fibers for specialized use sold for as much as $3000 per meter.[33] Space-manufactured ZBLAN could, in principle, revolutionize these markets because, as Randy Giles, chief scientist at the Center for the Advancement of Science in Space noted, manufacturing in space would "remove the convection buoyancy, and sedimentation, [allowing] materials that you bring back [to be] your gold standard."[34] Specifically, ZBLAN cables manufactured in microgravity experienced less crystallization, decreasing signal loss by orders of magnitude. By some estimates, 2,000-km length of ZBLAN fiber could have the same optical loss as 10 km of silica fiber.[35] Dennis Tucker, a materials scientist at NASA's Marshall Space Flight Center explained MIS's interest in manufacturing these cables, remarking that, "the reason they're doing this is the huge payout, which would be in billions of dollars if you can actually draw the fiber at least an order of magnitude better than silica."[36]

Although an exciting prospect, producing ZBLAN in space was a challenge, even for MIS. As of 2017, MIS was capable of producing no more than 50 meters of fiber using its module on the ISS, while the company estimated that addressing terrestrial markets would require producing thousands of kilometers annually. Achieving such scale would require large fixed capital investments.

In addition, the business case for ZBLAN was uncertain. While the anticipated demand for ZBLAN seemed promising, the myriad of potential applications (see **Exhibit 7** for example application areas for exotic optical fibers and glasses) meant MIS would have to be strategic about addressing the correct market segment, considering its limitations in production capacity. The company assessed three possible scenarios, comparing system costs, pricing, and demand for various assumptions about market capture, production targets, and production capacity (see **Exhibit 8** for a detailed breakdown of these three scenarios). Scenario 1, "Telecommunications Focus" required high throughput to address the growing demand for telecommunications products and assumed 5% capture of the projected global market for optical fiber in 2023. While expected revenue would be relatively high, MIS would have to launch, process, and return 0.402 cubic meters of ZBLAN -- much more than they had produced in the past. The other scenarios, Scenario 2, "Chicago Booth Projection" and Scenario 3, "Limited Market Penetration" both assumed more conservative estimates of ZBLAN production and focused on optimizing production for optoelectronic devices and specialty customers with stricter product requirements. Scenario 3, however, as opposed to Scenario 2, assumed a more conservative growth environment and placed an upper limit on how much revenue could be generated from specialty customers alone.

Production for use in space

If the space economy's development was to proceed as far as optimists projected, it would produce not only for export but also to meet its own internal demand. MIS hoped to be a key supplier and thus a key contributor to creating such markets in space, for space. In the late 2010s, it pursued two specific ideas.

One idea was to produce items on the ISS that would then be launched from it. Co-founder Dunn saw substantial potential in this idea: "[it] turns out, the ISS is a perfect platform for launching things into low-Earth orbit. Already our printers can print the cube portion of a CubeSat, and we've also printed the electronics in our lab. It's hard to say for sure, but around 2025, we should be able to print electronics aboard the ISS. This means we'll be able to email hardware into space for free, rather than paying to have it launched there."[37] The company began an initial attempt at commercializing this idea, partnering with ISS commercial contractor NanoRacks to develop an "orbital construction-and-deployment service for CubeSats (see **Exhibit 9**). MIS CEO Rush believed this could be a "fundamental shift for satellite production", envisioning a future where "satellites will be manufactured quickly and to the customer's exact needs, without being overbuilt to survive launch or [having] to wait for the next launch."[38]

A second idea—called Archinaut (a combination of *archi*tetcture and astro*naut)*—cemented MIS's place at the center of efforts to build out space infrastructure. In 2016, having proven the basic technology needed to validate additive manufacturing in space, MIS began developing the technology to print full structures, including electronics, in the vacuum of space. Archinaut would be a demonstration of the first additive manufacturing, aggregation and assembly of large and complex spacecraft systems on orbit.

As with its earlier efforts, MIS's Archinaut strategy was tied to NASA, this time through the agency's 2016 "Tipping Point Program" solicitation for in-space manufacturing. The Tipping Point Program was founded to fund companies working on technologies with both NASA and commercial space applications that could "result in a significant advancement of the technology's maturation, high likelihood of infusion into a commercial space application, and significant improvement in the ability to successfully bring the technology to market."[39] In particular, Tipping Point solicitations were intended to invite smaller companies to address significant challenges in the industry. As Dayna Ise, a NASA program executive, remarked, "We love our established space companies…but we also like to involve these sorts of recent new entrants into the space industry...these partnerships allow us to develop and prove these critical space technologies, and it's really been a successful model for us."[40] The program used fixed-priced contracts that included milestone payments and required a minimum 25% corporate or customer contribution. For ISM technologies, NASA would issue three Tipping Point contracts, to Orbital ATK, Space Systems Loral, and $20 Million to Made In Space for Phase I of the Archinaut Program.[41]

NASA shared MIS's vision for a broad range of applications—both near-term and long-range—of in-space manufacturing. The agency saw benefits such as "enabling remote, in-space construction of communications antennae, large-scale space telescopes and other complex structures; enabling small satellites to deploy large surface area power systems and reflectors that are currently reserved for larger satellites; eliminating spacecraft volume limits imposed by rockets; and, avoiding the inherent risk of spacewalks by performing some tasks currently completed by astronauts."[42] An even grander vision was expressed by Jim Reuter, associate administrator of NASA's Space Technology Mission Directorate, who stated, "in-space robotic manufacturing and assembly are unquestionable game-changers and fundamental capabilities for future space exploration... by taking the lead in the development of this transformative technology, the US will maintain its leadership in space exploration as we push forward with astronauts to the Moon and then on to Mars."[43] (See **Exhibit 10** for NASA's in-space manufacturing roadmap).

NASA's support of MIS's role in pursuing this broad vision for in-space manufacturing was made clear when, in 2019, it awarded the company an additional $73.7 million for a project called Archinaut One. NASA Administrator Jim Bridenstine referred to the Archinaut One technology as "game-changing" during a tour of the manufacturing facility.[44] Slated for a 2022 launch date, Archinaut One would manufacture two ten-meter long wings of solar arrays for use by a small satellite. Producing solar arrays in space was a natural first demonstration project, as the standard approach of unfolding pre-attached, smaller solar panels had been a significant limitation for in-space assets, especially satellites. MIS hoped its solar arrays would generate "as much as five times more power than traditional solar panels on spacecraft of similar size."[45] Prior to receiving the grant, MIS had completed ground-based demonstrations of the technologies, and it planned to use the NASA funding to build the required spacecraft, test it on ground, and then deploy it into space.

If successful, Archinaut One would demonstrate the potential of in-space construction of items like large scale space telescopes and other complex structures. Andrew Rush, CEO of MIS remarked that, "for us, this is one of those watershed moments that takes this technology and propels it into the next stage."[46] In 2019, Made In Space had plans to expand its workforce from 40 employees to nearly 100.

Made In Space: Writing Act III

Although the company got its start with comparatively straightforward technologies for use in LEO, MIS co-founder Mike Chen believed these technologies could be the bedrock of something much more ambitious, remarking, "imagine being able to colonize a distant planet by bringing nothing but a 3D printer and some mining equipment. It might sound like science fiction, but the first steps toward making it a reality are happening in our lab right now, and aboard the ISS."[47] In the industry, the company was known for setting ambitious goals, but, as explained by Tech Crunch journalist Jon Evans, it consistently delivered and demonstrated sound technologies, and "given their accomplishments, Made In Space earned the right to be taken seriously."[48]

MIS's mission statement was to "pioneer sustainable space infrastructure to support our customers' missions, promote national security and drive exploration objectives through advanced space manufacturing." Rush often interpreted this vision in an ambitious sense, aiming for MIS to ultimately "enable people to sustainably live and work in space, and incentivize permanent settlement, recognizing that manufacturing will be a key piece."[49] He went on to say that MIS "absolutely wants to build roads and commodes for human exploration and settlement for the on, Mars and beyond", stating that the vision is "a very human settlement-focused vision."

While the leap from printing a wrench on-board the space station to printing space infrastructure for new settlements may have seemed enormous, Rush pointed out that "the underpinning technology, that ability to do 3D printing in microgravity really remained the same."[50] MIS had proven key technologies through the initial NASA SBIR grants, namely, the ability to manufacture, assemble, and integrate in microgravity and vacuum of space. Once these hurdles were overcome, anything (in principle) could be built in space. Peter Diamandis commented on this strategy, remarking that, "while Made In Space started off disrupting a billion-dollar space parts industry, the exponential growth curves that underpin their business model [led] them directly toward first mover advantage in the multitrillion-dollar industry that will eventually be off-world living."[51]

June 2020 brought a sudden twist to the story of Made In Space, when Redwire – a company formed three months earlier by the merger between the private equity firm AE Industrial Partners and space components manufacturers Adcole Space and Deep Space Systems – announced that it was acquiring Made In Space. In a press release, Redwire described itself as a "new leader in mission critical space solutions and high reliability components for the next generation space architecture." Steve Bailey, President of Deep Space Systems, framed it as a "one-stop shop for complex space exploration products and services."[52]

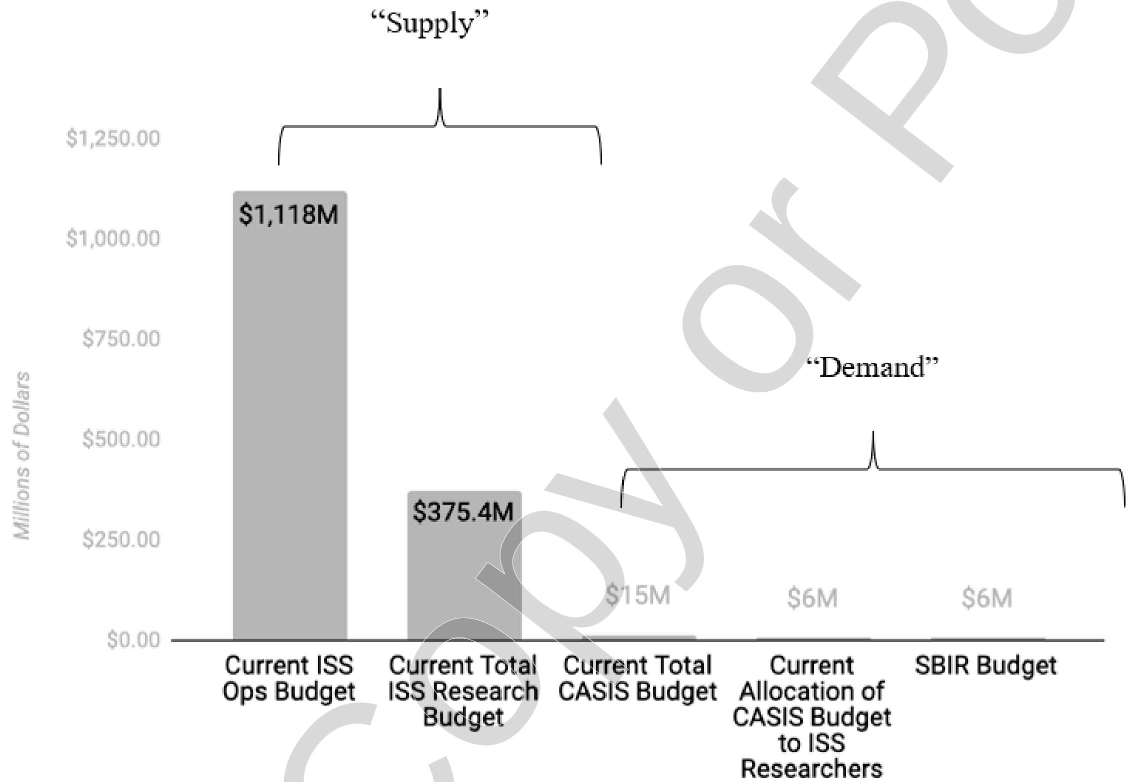
Redwire's acquisition of Made In Space indicated a step towards greater vertical integration and ownership of the space supply chain. As part of the acquisition, Andrew Rush became chief operating officer of Redwire, while Mike Snyder assumed the chief technology officer position at Redwire. Rush said of the acquisition: "Joining Redwire is an exciting opportunity to be part of a new company taking an innovative approach to address the needs of today's space industry…Redwire provides us with the scale and space heritage we need to take our technology to the next level.[53]

Exhibit 1 Loads Experienced during Launch, compared with Forces in Microgravity

Loading Type	Launch Loads	In-Space Loads
Quasi-Static Acceleration	3.7 to 6.6 g	Drag: 10^{-7} g Gravity gradient: 0.3×10^{-6} g/m
Sine Vibration	5 Hz: 0.5 to 1 g 100 Hz: 0.8 to 1 g	<6 Hz: 8.4×10^{-6} RMS 100 Hz: 1×10^{-3} g RMS
Acoustics	130.8 to 144.7 dB OASPL	Negligible

Source: James Patton Downey. A Researcher's Guide to: International Space Station Microgravity Materials Research. Technical Report, NASA, Houston, TX, 2015.

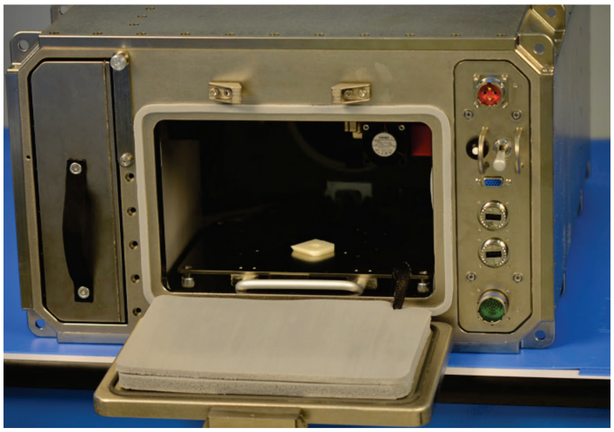
Exhibit 2 International Space Station (ISS) Operations Costs and Demand



Source: Presentation by Lynn Harper, Lead for Investigative Studies, NASA Headquarters

Note: Costs are annual. The ISS "supply" costs here do not include the ~$100 Billion in costs to build and launch the ISS.

Exhibit 3 Additive Manufacturing Facility (AMF) Photos and Specifications



AMF Specifications	
Print Volume (mm)	140 L x 100 W x 100 H
Device Dimensions (mm)	566.5 x 460.4 x 273.2
Weight	45 Kg (on Earth)
Power Usage	600 W

Source: Made In Space. "Additive Manufacturing Facility." Accessed May 5, 2020. https://madeinspace.us/capabilities-and-technology/additive-manufacturing-facility/.

Exhibit 4 Example of Tools Considered for Printing Using the AMF

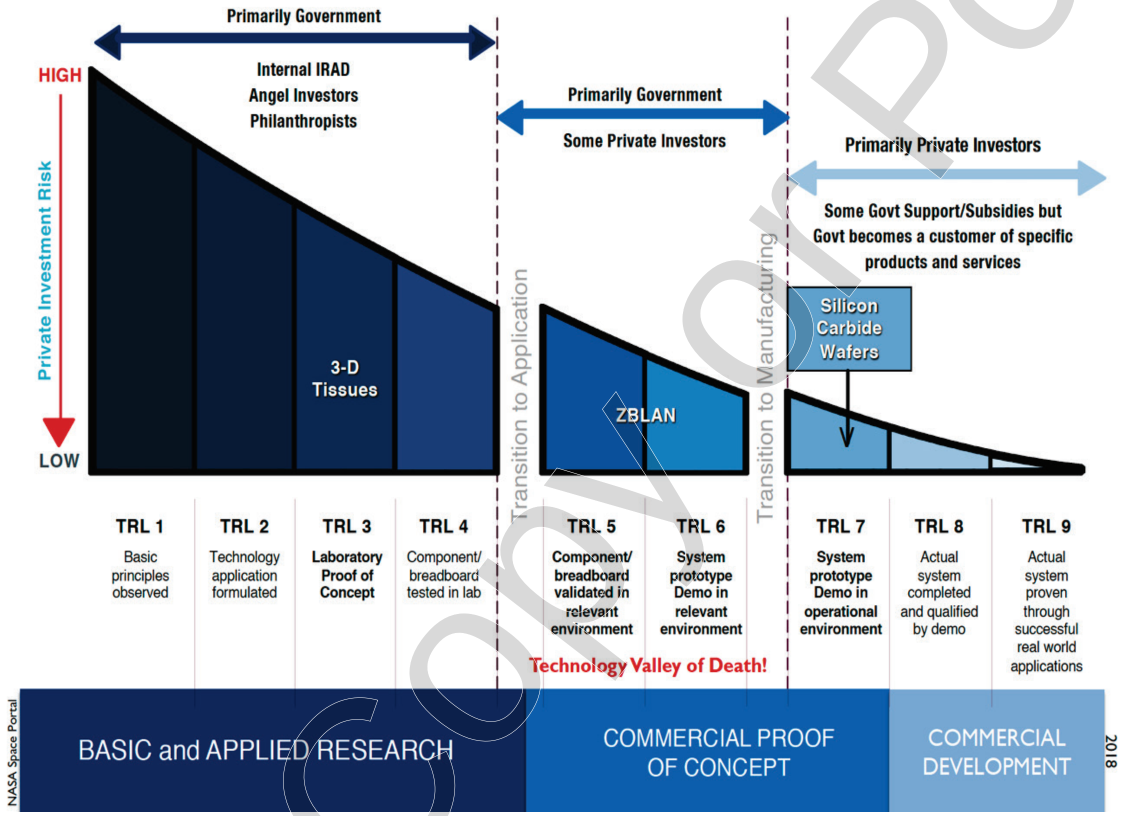
Source: Made In Space. "Additive Manufacturing Facility." Accessed May 5, 2020. https://madeinspace.us/capabilities-and-technology/additive-manufacturing-facility/.

Exhibit 5 Made in Space Timeline and Funding

Year	Funding	Milestones
2019	**$75,472,000** *(Tipping Point + SBIR)*	**February 2019** NASA grants MIS Tipping Point Solicitation to fund Archinaut - $73.7 Million[54] MIS earns the Guinness Book World Record for "World's Longest 3D printed non-assembled piece" [55]
2018	**$3,621,008 (***SBIR)*	
2017	**$518,075 (***SBIR)*	**December 2017** MIS launches Made In Space Fiber Optics device to ISS to manufacture ZBLAN optical fiber[56]
2016	**$20,000,000 (***Tipping Point)*	
2015		Andrew Rush appointed CEO and President of MIS. [57]
2014	**$244,126 (***SBIR)*	**December 2014** MIS and NASA remotely operate the printer for the first time, manufacturing a ratchet. **September 2014** MIS Zero-G printer launched to the ISS[58]
2013	**$946,776 (***SBIR)*	
2012	**$128,821 (***SBIR)*	
2011		**May 2011** MIS Granted NASA Flight Opportunities Contract[59]
2010		**August 2010** Made In Space founded

Source: Compiled by casewriter from NASA SBIR funding data60 and Made in Space website[61].

Exhibit 6 Technology Readiness Level of ESO-identified Technologies



Source: Presentation by Lynn Harper, Lead for Integrative Studies, NASA Headquarters.

Exhibit 7 Application Areas and Examples for Exotic Optical Fibers and Glasses

Table 1. Application Areas and Examples for Exotic Optical Fibers and Glasses

Application Area	Examples
Medical	Light guides, imaging tools, and lasers for surgery
Defense/government	IR countermeasures, stand-off detection of explosion hazards, eye-safe seekers for smart munitions, covert communications systems
Information technologies	Data transmission
Fiber lasers	Plastic and polymer processing, spectroscopy, noninvasive medical diagnosis, remote sensing
Telecommunications and networking	Connect users and servers in a variety of network settings and help increase the speed and accuracy of data transmission.
Industrial/ commercial	Imaging in hard-to-reach areas, (wiring where electromagnetic interference is an issue); sensory devices to make temperature, pressure, and other measurements; nondestructive testing

IR, infrared.

Source: Cozmuta Ioana, and Rasky Daniel J. "Exotic Optical Fibers and Glasses: Innovative Material Processing Opportunities in Earth's Orbit." New Space, September 1, 2017. https://doi.org/10.1089/space.2017.0016.

Exhibit 8A Scenario 1 Market Segment Analysis: "Telecommunications Focus"

	Telecom Fiber	Optoelectronic Devices	Specialty Applications	Total Production
Capture Share[a]	95%	3%	2%	-
Price Per Meter[b]	$6[c]	$50	$150	-
Production to Meet Demand (km)	47,500.00	180.00	40.00	47,720.00
Annual Preform Demand (kg)	21,590.91	81.82	18.18	21,690.91
Monthly Production (km)	3958.33	15.00	3.33	3,976.67
Monthly Preform Demand (kg)	1799.24	6.82	1.52	1,807.58
Annual Segment Revenue (Millions)	$285	$9	$6	-

Source: Made In Space

Note: This scenario assumes 5% capture of the projected global market for optical fiber in 2023, anticipating growing demand for telecommunications products.

[a] Capture Share refers to a percent of Made In Space's production portfolio, not the overall market. Current fiber market segmentation by sales is around 50% for telecommunications, 30% for optoelectronic devices, and 20% for specialty applications.

[b] Prices reflect the necessary rates determined by MIS to be competitive with silica fiber and other exotic fibers.

[c] Telecommunications fiber is high-throughput basic ZBLAN, the low price comes from benefits from mass-production economies of scale.

Exhibit 8B Scenario 2 Market Segment Analysis: "Chicago Booth Projection"

	Telecom Fiber	Optoelectronic Devices	Specialty Applications	Total Production
Capture Share	0%	80%	20%	--
Price Per Meter	$0	$20[a]	$150	$46.00
Production to Meet Demand (km)	-	548.80	137.20	686.00
Annual Preform Demand (kg)	-	249.45	62.36	311.82
Monthly Production (km)	-	45.73	11.43	57.17
Monthly Preform Demand (kg)	-	20.79	5.20	25.98
Annual Segment Revenue (Millions)	$0.00	$10.9	$20.5	$31.5

Source: Made In Space

Note: This scenario assumes an annual production rate of 686km of fiber. This rate of production is consistent with the demand expected from optoelectronic devices and specialty customers, and unable to satisfy demand from telecommunications customers.

[a] The lower price per meter as compared with Scenario 1 assumes fierce competition from terrestrial fiber sources.

Exhibit 8C Scenario 3 Market Segment Analysis: "Limited Market Penetration"

	Telecom Fiber	Optoelectronic Devices	Specialty Applications	Total Production
Capture Share	0%	80%	20%	
Price Per Meter	$0	$20	$125	$41
Production to Meet Demand (km)	-	192	48	240
Annual Preform Demand (kg)	-	87.27	21.82	109.09
Monthly Production (km)	-	16	4	20
Monthly Preform Demand (kg)	-	7.27	1.82	9.09
Annual Segment Revenue (Millions)	$0.00	$3.8	$6	$9.8

Source: Made In Space

Note: This scenario assumes a conservative estimate for the addressable market for microgravity ZBLAN fiber at $10 million per year due to technological changes in terrestrial fiber optics industry that mitigate the competitive advantages of ZBLAN fiber and drops in prices for fiber for specialty applications.

Exhibit 8D Scenario Comparisons

	Scenario 1	Scenario 2	Scenario 3
Capital Investment	180[a]	30	10[b]
Monthly Costs (Millions)	$21	1.8	0.6
Monthly Revenues (Millions)	$25	$2.5	0.820
Time to Breakeven	46 months	39 months	59 months

Source: Made In Space.

[a] The capital investment in Scenario 1 is high due to the high production needed to meet demand, necessitating a large facility.

[b] The production rate in Scenario 3 is feasible with a system derived from the MIS hardware already deployed to the ISS, as such it requires lower additional capital investment.

Exhibit 9 MIS and NanoRacks "Stash & Deploy" Program

13. Stash & Deploy

Through a partnership with Nanoracks, Made In Space will use the AMF to print satellite structure. NanoRacks will supply satellite components, enabling on-demand satellite deployment capabilities.

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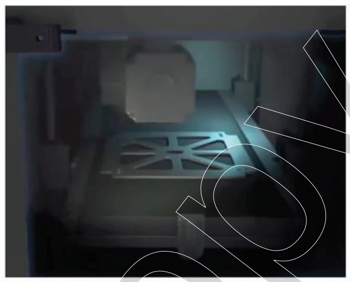
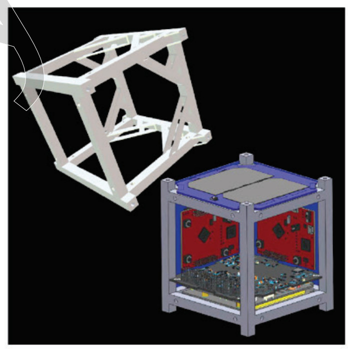
NANORACKS

1 NanoRacks launches modular CubeSat components to ISS. Satellite developers on Earth can use this inventory of "stashed" components for their CubeSat designs.

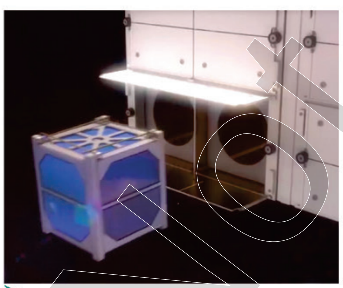
2 Once a CubeSat design is finalized, an optmized CubeSat structure will be 3D printed on station.



3 The printed structure for that CubeSat is then integrated with the pre-selected stashed components.



4 The resulting integrated and assembled CubeSat is then launched into space by NanoRacks.

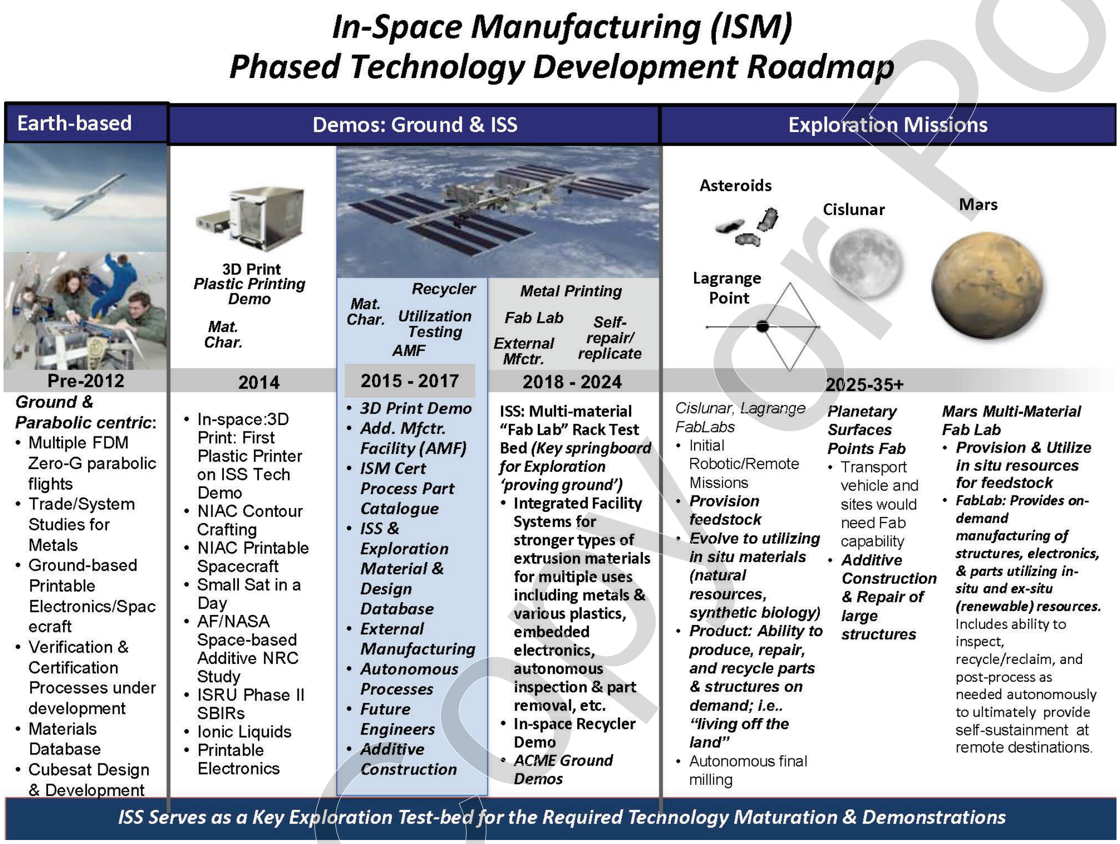


5 The partially 3D printed CubeSat enters into Low Earth Orbit along a trajectory that avoids any possible collision with the ISS.

6 When the CubeSat reaches a safe distance from the ISS, the power systems are turned on and the Satellite begins operation.

Source: Made In Space. "Additive Manufacturing Facility." Accessed May 5, 2020. https://madeinspace.us/capabilities-and-technology/additive-manufacturing-facility/.

Exhibit 10 NASA In-Space Manufacturing Roadmap



Source: Werkheiser, Niki. "In-Space Manufacturing: Make It, Don't Take It!" October 7, 2017. https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20170009900.pdf.

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