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Financing Astroscale

In January 2016, Nobu Okada was actively pursuing several leads with venture capital investors across Japan, Singapore and the U.S., in an effort to raise a $35 million Series B round of financing for his startup, Astroscale. Less than three years before, in May 2013, Okada had founded Astroscale to pursue a bold vision: developing a business to help mitigate the potentially catastrophic effects of space debris on the burgeoning space industry, and ultimately to help make space "sustainable".

Experts had grown increasingly concerned about adverse effects of space debris in recent years but no compelling solutions were on the horizon. According to the U.S. Space Surveillance Network (SSN),[1] an estimated 500,000 particles between 1 and 10 cm, and over 100 million particles smaller than 1 cm in Low Earth Orbit (LEO) were orbiting the earth in 2015. (See **Exhibits 1** and **2** for number and class of objects in space.) With speeds of around 18,000 miles per hour— almost 7 times faster than a bullet[2] — the destructive potential of these objects was enormous: a piece of space debris the size of a cherry traveling at a typical orbital velocity carried the force of an exploding grenade.[3] Even tiny fragments (smaller than 1 cm) were able to severely damage satellites and could be potentially lethal for astronauts. Making matters worse was the possibility of a domino effect in which collisions between satellites and space debris created more debris, which in turn created more collisions, and so on. As NASA scientist Donald Kessler pointed out in 1978, the worst-case scenario was that this domino effect would cause LEO to reach a tipping point beyond which collisions were ever increasing and unstoppable, so that no satellites would survive.

This so-called Kessler Syndrome was not merely hypothetical. Neil deGrasse Tyson, director of the American Museum of Natural History's Hayden Planetarium, warned: "The total satellite destruction scenario—it's real."[4] In fact, despite extensive tracking networks put in place by international space agencies, nobody seemed to notice two satellites hurtling toward each other at a relative speed of 22,300 mph some years before. On February 10, 2009, an active U.S. communications satellite (Iridium 33) exploded on impact with a defunct Russian satellite (Kosmos 2251), spewing 2,200 trackable objects—those larger than 10 cm in diameter—and hundreds of thousands of smaller, undetectable fragments into Earth's orbit. Just two years earlier, a Chinese weather satellite (Fengyun-1C) was destroyed by a kinetic kill vehicle traveling at nearly 18,000 mph as part of China's anti-satellite ballistic missile test, creating over 2,000 pieces of trackable objects and an estimated 150,000 smaller fragments.

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Officials responsible for mitigating the threat from space debris expressed a mixture of urgency and caution. The National Research Council of the U.S. National Academy of Sciences published a report in 2011 stating, "[T]he current orbital debris environment has already reached a 'tipping point.'"[5] In November 2015, NASA Administrator Charles Bolden said: "The answer's going to be debris removal, and we've got to figure out how to do that. And we are not doing sufficient work on it right now."[6] However, Bolden's message was tempered by Jer Chyi Liou, Chief Scientist of NASA's Orbital Debris Program Office, who said, "The sky is not falling at least in the foreseeable future. We do have time to develop the technology. We don't need to go out and remove debris in the next five years or so—10 or 20 years, maybe."[7] Nevertheless, a wide range of experts seemed to agree that space debris would eventually require a solution, and developing that solution would take time. According to Donald Kessler himself, however, "The cascade is happening right now [2013]—the Kosmos-Iridium collision was the start of the process. It has already begun."[8]

Over the two and half years since founding Astroscale, Okada had hired a team in Tokyo and Singapore, raised nearly $8 million in a Series A round of funding, and partnered with a Japanese chemical company to develop an innovative adhesive-based approach to Active Debris Removal (ADR). The adhesive would be mounted on a satellite and used to capture orbiting space debris. The satellite would slow the captured debris, pushing it into a lower orbit and causing it to re-enter Earth's atmosphere, where it would disintegrate harmlessly. Having developed the key technological elements of his business, Okada was looking to raise $35 million in Series B financing to provide an in-orbit demonstration of the technology.

Trying to create a small Singaporean start-up to solve a problem of immense technological complexity ahead of the world's most advanced scientific and national security agencies may have seemed quixotic. After all, neither NASA nor the Pentagon was willing to spend even a small fraction of their budget (which, added together, would have been at least five orders of magnitude greater than Astroscale's) on ADR. Was Okada likely to succeed? Even if he could succeed technologically and create immense value, could Astroscale capture a large enough portion of it to justify an investment by a for-profit investor? As Okada pondered these questions, he also reflected on which investors would have the vision and staying power to pursue his bold ambition, and how he could convince them to put their money behind Astroscale.

The Space Age, Satellites, and Space Debris

The Soviet Union's 1957 launch of Sputnik, the world's first artificial satellite, "marked the start of the Space Age,"[9] a new era of human history in which exploration of the universe beyond Earth became possible. Over the next six decades, among other highlights, the Apollo missions landed humans on the moon, numerous probes reached and photographed the far reaches of the solar system, space-based equipment studied deep space for cosmological clues, and the International Space Station (ISS) was constructed by a consortium of countries to establish a permanent human presence in space.

It was fitting that the Space Age started with a satellite, because the economic implications of humanity's access to space were centered on a rapidly expanding array of telecommunications, locational, and observational satellites in Earth orbit. In the six decades after Sputnik, more than 4,800 rocket launches had placed over 6,000 satellites into orbit,[10] of which 1,381 remained operational by the end of 2015 (see **Exhibit 3** for a more detailed breakdown of satellites by function).[11]

Projections suggested that the number of satellites was about to grow dramatically, driven by technologies that were lowering costs of production and launch, coupled with increasing demand to access space. In terms of technological progress, sophisticated manufacturing processes such as

computational fluid dynamics, computer-aided design and manufacturing, robotic assembly, and welding techniques had become ubiquitous. Advanced composite materials achieved superior performance at lower cost. "Just 10 years ago, space was the exclusive province of governments and large contractors," noted Sunil Nagaraj, vice president of Bessemer Venture Partners. "Due to standardization such as the CubeSat format as well as cost reductions driven by the consumer electronics industry, satellites can now be built and launched for $200,000 to $400,000. Zooming out, a space startup can now build and launch a constellation of SmallSats for about the same amount of capital that a tech startup can build and launch a mobile app — that's an absolutely amazing fact!"[12]

SpaceX, a company manufacturing and launching rockets, had been widely credited with lowering the cost of satellite launches. For example, commercial operations contracting with the European or Russian Space agencies typically paid between $100 million to $260 million for a single launch. On the other hand, SpaceX charged somewhere between a half and a third this cost for a comparable satellite, due to its modular design and engineering choices.[13] Smaller satellites could "hitchhike" to space at $30,000 to $50,000 a kilogram, enabling a 5 Kilogram "nanosatellite" to be launched into Low Earth Orbit (LEO) for under $250,000. Reusability of launching rockets was perhaps the most important technological advance on the horizon. Elon Musk, founder and CEO of SpaceX noted that "If one can figure out how to effectively reuse rockets just like airplanes, the cost of access to space will be reduced by a factor of a hundred. A fully reusable vehicle has never been done before. That really is the fundamental breakthrough needed to revolutionize space."[14] Blue Origin, founded by Amazon CEO Jeff Bezos was also in the process of developing a fully reusable, vertical takeoff, vertical landing (VTVL) vehicle. SpaceX reached an important milestone in December 2015 when, ten minutes after launching, its Falcon 9 rocket landed back at Cape Canaveral Air Force Station after successfully putting 11 small satellites into orbit.

In addition to technologies making it cheaper to access space, a number of factors suggested that demand for space missions would continue to grow (see **Exhibit 4** for a breakdown of Space Industry revenues). Space tourism was a major source of enthusiasm in the industry, pioneered by startups such as Virgin Galactic that charged approximately $200,000 for a flight to 55,000 feet. While providers of telecommunications, media, Internet and other services requiring satellites in space had always been dominant players in the space industry, a new source of demand appeared in 2004, when the Federal Aviation Administration (FAA) began granting commercial licenses and permits to more private companies, paving the way for a commercial space industry. The commercial space industry was still nascent, but spanned concepts such as asteroid mining and space hotels to manufacturing products such as fiber optics, semi-conductor chips and certain drugs that were harder to produce on earth with the same fidelity.[a]

Growth in ubiquitous connectivity was also driving important changes in the satellite industry. In October 2015, OneWeb, a global broadband services provider, announced a plan to place a 720-satellite constellation in space to provide high-speed Internet anywhere in the world.[15] SpaceX, a private rocket and spacecraft manufacturer and launch company, had secured $1 billion in January 2015 to launch 4,000 satellites.[16] And Samsung, a Korean technology conglomerate, was reported to be developing a 4,600-satellite network. These constellations would be comprised of smaller satellites – from a few kg to 500 kg as opposed to traditional and heavier Geosynchronous communications satellites that were upwards of 500 Kg – working as a cluster in LEO. (see **Exhibit 5** for example of such constellations and **Exhibit 6** for projected growth in 1-50 Kg. satellite launches).

[a] The discussion of the New Space sector and its rise draws from Matthew Weinzierl and Angela Acocella, "Blue Origin, NASA, and New Space (A)," HBS No. 716-012 (Boston: Harvard Business School Publishing, 2016).

The proliferation of satellites and other commercial operators highlighted and exacerbated the threat of space debris to the global economy. A typical communications satellite's operational life span was 5 years, but each satellite could take upward of 20 years to naturally deorbit. As a result, only 5% of the 23,000 objects tracked in LEO by the SSN were operational satellites.[17] The rest were space debris, including derelict satellites and spacecraft, upper stages of launch vehicles, carriers for multiple payloads, mission-related items from space activities, and fragments from in-orbit breakups and collisions (see again **Exhibit 1**). Of course, satellites were vulnerable to this debris, and with an increasingly crowded array of satellites planned for LEO, the likelihood of collisions—and the dreaded Kessler Syndrome—would only increase. In 2013, experts estimated that the "current population of man-made objects in LEO has reached a critical density that will lead to a slow but unstoppable cascading effect . . . primarily driven by catastrophic collisions that are likely to occur every five to nine years."[18]

At the same time, the expansion of a destructive debris belt in LEO could prevent space exploration missions beyond LEO, including to the moon and Mars, and put at risk the nascent space tourism and commercial space sector. In July 2015, those aboard the ISS were forced to evacuate to the emergency Russian escape capsule when space agencies observed that a piece of debris traveling at almost 30,000 mph would breach the ISS safety zone with only 90 minutes of warning, too short a time span to initiate debris avoidance maneuvers.[19]

Debris Mitigation

In the late 20th and early 21st centuries, efforts to solve the tragedy of the orbital commons focused, , on not making the problem worse. Governments and their space agencies focused on (1) tracking existing debris so as to avoid collisions with satellites they could maneuver and (2) developing regulations and guidelines under which satellite operators would voluntarily design their equipment to take itself out of orbit after its useful life. In the U.S., for example, NASA established the Orbital Debris Program Office in 1979 to lead research on measurement and mitigation of space debris, and in 1995 the office published the first set of mitigation guidelines. In 2002, the U.S. Inter-Agency Debris Coordination Committee (IADC) published the "IADC Space Debris Mitigation Guidelines."

International mitigation efforts culminated in the work of the 2007 United Nations (UN) Committee on the Peaceful Uses of Outer Space (COPUOS). Its "UN Space Debris Mitigation Guidelines" were approved by the UN General Assembly and adopted by the 63 UN member nations as voluntary high-level mitigation measures.[20] These guidelines not only described mitigation measures for limiting debris released during normal operations but also implemented a 25-year rule. In accordance with this rule, upper-stage rockets and retired satellites were to re-enter the atmosphere within 25 years of their launch.[21] Just four years later, the International Organization for Standardization (ISO) issued ISO 24113 to ensure that spacecraft and launch vehicle orbital stages were designed, operated, and disposed of in a manner that prevented them from generating debris throughout their orbital lifetime.[22]

While the implementation of early mitigation guidelines slowed the growth of space debris, the 2007 Chinese anti-satellite test and the 2009 Iridium-Kosmos collision erased any gains and prompted further action both internationally and within individual countries. The U.S. Department of Defense's Joint Space Operation Center, which operated the SSN, began alerting satellite operators and space agencies of critical approaching debris. The French Space Operation Act and the Japanese Space Basic Law, both enacted in 2008, and the U.S. National Space Policy, issued in 2010, set debris minimization as national objectives.[23,24,25]

The private sector responded to the demand for mitigation solutions. One example was D-Orbit, an Italian company founded in 2011 with a mission to ensure "clean and safe access to space." D-Orbit developed a disposal system to be installed on satellites before launch that would facilitate a controlled decommissioning of the spacecraft.[26] Another push from the private sector came from the Commercial Space Operations Center (ComSpOC) of Analytical Graphics Inc. (AGI), a company that developed commercial modeling analytics software and sensing capabilities used to track objects in space. Launched in 2014 to track active satellites and other space objects, ComSpOC used commercially available radar sensors and purchased observational data to provide commercial and government satellite owners and operators with tracking services and an object catalog called SpaceBook.[27]

Despite this policy cooperation on debris mitigation, officials were clear that mitigation would not adequately control the future growth of space debris. In 2011, the U.S. Defense Advanced Research Projects Agency (DARPA) published the "Catcher's Mitt" report, which advocated removing 5 to 10 large pieces of debris per year to minimize collision risks.[28] In November 2015, NASA Administrator Charles Bolden said: "Not a lot of countries are putting money into debris removal development, and more of us need to. We are among those that're not putting a lot of money into debris removal. We work a lot on what we call debris mitigation. . . . But that's not the answer."[29]

Active Debris Removal

According to a 2006 report by NASA's Jer Chyi Liou, without effective cooperative action to remove debris—not just stop its further production—the prospects for space debris looked bleak. Liou's report, "Instability of the Present LEO Satellite Populations," noted that even if all planned and future launches immediately ceased, collisions in LEO would continue to occur for 200 years. Liou was not alone in his judgment. Findings from a simulation of the LEO debris environment by the IADC consortium of six space agencies—NASA, the European Space Agency (ESA), and agencies from India, Japan, Italy, and the UK—also suggested that LEO had reached the critical density and that the orbital debris mitigation measures adopted by the international space community were inadequate in stabilizing the orbital debris environment.[30]

Public pressure also mounted to develop ADR technologies, and private-sector funding sources began to emerge. The XPrize Foundation, home of the Ansari XPrize (for private space access) and the Google Lunar XPrize (to land a robot on the moon), asked its online community to vote on future prizes. An orbital debris removal proposal had reached over 1,000 votes by December 2015, placing it in the top 3 of 50 challenge ideas, making it more popular than ideas for renewable energy storage and distribution, cancer detection, and invisibility.[31]

Despite the seeming momentum toward ADR, actual investments in the technology remained muted. A number of challenges appeared to be preventing progress. Nobu Okada blamed the inaction, at least in part, on lack of public awareness: "Existing space organizations such as NASA must follow the political will of the people. Space agencies will continue working on a project as long as taxpayers say it is worth spending on. This issue [space debris removal] doesn't have good public awareness, so governments do not allocate funds." Philippe Moreels, Head of Strategy and Business Development at Astroscale added that "governments do not allocate budget to ADR because the debris issue is filled with uncertainty. No one is able to tell when a collision will happen and what exact impact will. This uncertainty creates inaction on the part of governments."

Another explanation was that the technology for ADR was too expensive relative to the current extent of the risks from debris. Wade Pulliam, lead researcher on the Catcher's Mitt study, said, "We have to start thinking about developing the technology [for debris removal] but then we should leave

it on the shelf. It's not worth deploying it now."[32] Liou himself noted, "As of today, there is no economically viable and technically feasible method to allow us to do it."[33] He continued, "The debris population continues to grow and there's no sign of slowing down. Before we can get to ADR, we need to improve the global mitigation efforts. Once we do that, we can figure out the removal options. It may take us 10–20 years to develop the cost-effective technology. These are very difficult problems, and there's no commercial incentive to develop the technology to remediate the orbital debris environment."[34]

Among the many technological obstacles to ADR, securing an uncooperative, spinning target traveling at over 18,000 mph was particularly challenging. According to Dr. Alvar Saenz-Otero, director of the MIT Space Systems Lab, a controlled rendezvous interaction with the spinning object was a substantial challenge: "Things in space behave differently than on the ground. Understanding the object's nutation [or movement] in space is not trivial. And the debris you're capturing is going to pull you."[35] Space agencies, academic research institutes, and private companies tested various capture technologies, but their development efforts had so far resulted in few promising options.

ADR was considered a dual-use technology for both civilian and military purposes, such as deorbiting or destroying other countries' satellites (as dramatically demonstrated by the 2007 Chinese anti-satellite test). Defense experts predicted that the next world conflict would involve a series of geopolitical events culminating in the obliteration of enemy communications and spy satellites, crippling vital military capabilities. "We are dealing with a fact and reality that you cannot ignore space as a sovereign nation," said Jeremy Greaves of the Airbus Group.[36] Countries were reluctant to facilitate cooperation on ADR if it would mean sharing sensitive security information. Relatedly, the legal implications of capturing uncooperative objects could pose significant barriers. If damage to other space assets occurred during ADR operations, who would be liable for the damages?[37]

Inevitable Tragedy?

Ninety percent of the existing space debris had resulted from space activities of three countries: the U.S., Russia, and China, and many countries—especially those in the process of building up their own space programs—believed that the major powers should pay for debris removal. Whether governments should, or even could, finance the efforts alone remained a topic of contention as well. "The debris problem was largely created by governments using public money," wrote Brian Weeden, technical advisor for the Secure World Foundation. "Any funding of ADR activities is likely to come from public money and either be governments conducting missions themselves or purchasing services from [the] private sector."[38] "Several companies have proposed technologies hoping they have the technology that works best," said Raymond Sedwick, director of the Center for Orbital Debris Education and Research (CODER) at the University of Maryland.[39]

Along with Astroscale, firms such as Tethers Unlimited, Star Technology and Research (STAR), and Australia-based Saber Astronautics had proposed various ADR technologies.[40,41,42] "Let's say governments are interested in funding debris remediation and collectively decide to raise money for it—say by taxing launches. These companies want to be the first in line," Sedwick continued.[43] But, NASA's Chief Scientist for Orbital Debris Liou noted, tight government budgets would make it difficult to pay for ADR services even if they were readily available: "Some private companies are using their own internal funding to develop the ADR technologies, but if they are successful, they will still need to rely on governments to contract or buy their services. Based on today's technology, my opinion is that no single government can afford to support routine ADR operations for effective remediation by itself."[44]

Private satellite operators and defense agencies had the most to lose, given a growing incidence of collisions, with both valuable equipment and sensitive intelligence at risk, yet neither group was investing in debris removal measures. Weeden noted that with their substantial budgets, agencies and private operators still found it more cost-effective to design their satellites to maneuver and avoid collision rather than to remove threats. "Ninety percent of the total risk is the launch and early mortality due to manufacturing problems. The additional risk from on-orbit collisions is currently an insignificant amount of the total insurance and is not an incentive to pursue other options," he explained.[45]

In the end, a note of resignation was common among space experts. Marshall Kaplan, an orbital debris expert within the space department at Johns Hopkins University's Applied Physics Laboratory, described the seemingly futile situation:

> The proliferation is irreversible. Any cleanup would be too expensive. Given this insight, it is unlikely spacefaring nations are going to do anything significant about cleaning up space. . . . The fact is that we really can't do anything. We can't afford it. We don't have the technology. We don't have the cooperation. Nobody wants to pay for it. Space debris cleanup is a "growth industry," but there are no customers. In addition, it is politically untenable. . . . Barring the discovery of a disruptive technology within the next decade or so, there will be no practical removal solution. We simply lack the technology to economically clean up space.[46]

Nobu Okada and Astroscale

Born in Kobe, Japan, in 1973, Nobu Okada grew up with dreams of becoming an astronaut. In 1988, while attending high school, Okada participated in NASA's space camp, where he met Mamori Mohri, the first Japanese astronaut who had joined the U.S. space shuttle project and was training at NASA at the time Okada met him. Mohri, a national hero, presented Okada with a handwritten note containing the message "Space is a place where your generation shines."[47] Inspired by the message, Okada studied hard, hoping that one day he could make it to space.

Okada eventually gave up the dream of becoming an astronaut. "I almost forgot about space," he recalled. After graduating from the University of Tokyo with a degree in agricultural science, Okada joined Japan's Ministry of Finance. While employed by the Japanese government, Okada began an MBA program at Purdue University, which helped foster his entrepreneurial spirit. In the midst of the growing internet bubble of the late 1990s, Okada said, "every week two to three students would leave the program to start a company." Inspired by his classmates' aspirations but set on finishing his degree, Okada left the Ministry of Finance, paid back the debt he owed to the government for his partial education, and changed his student status to reflect that he would personally fund the remainder of his education.

After graduating from Purdue, Okada worked at McKinsey & Company and Bain Capital, building his strategy, business, and management skills. In 2004, he became chief financial officer of a software development and distribution company and was instrumental in its successful IPO. Okada's resulting capital gain allowed him to establish his own startup in 2009, developing and providing smartphone applications in Singapore. Okada ultimately sold the technology and patent rights to a Japanese company.

As Okada approached his 40th birthday and reflected on what he had learned from his recent entrepreneurial experiences, he began to wonder whether he was making enough of an impact on

society. "I was having a midlife crisis," said Okada. He then recalled his childhood dreams of space and the message he had gotten from Mohri, and he charted a new course:

> People whom I deeply respect had a similar life pattern: absorb knowledge and develop skills in their 20's, clarify their mission in their 30's and start implementing their mission in their 40's. Turning to 40, I thought I should follow my passion, which was to do something about space. In addition, I was convinced that the "Napster Moment" was coming to the space industry. It is a moment when a service which has been only for the limited number of people becomes one for everyone at once. And it is a now-or-never moment. Many "space entrepreneurs" will emerge and I wanted to be one of them.[48]

Founding Astroscale

Okada set out to learn as much as possible about the state of the space industry, attending conferences and speaking to government and academic experts. "I learned debris was a growing threat. I saw research and concepts, but I didn't see action. . . . In the IT industry, we develop a better version of something in three months. In the space industry, all the discussions focused on 'What shall we do over the next five to 10 years?'"[49] He soon realized that his and future generations could not shine in space, as Mohri had written, if space agencies, governments, and private companies could not construct a solution for the space debris issues. "When I found nobody solved this problem I thought 'This is a space I should enter,'" Okada said. Unsure about his inexperience in the field, Okada asked the advice of an expert from a prominent space firm: "He told me to set up a company. 'The space industry needs someone who is passionate about space but is from the outside, who has worked in a different industry before.'" Just three months later, in May 2013, Okada founded Astroscale, investing $200,000 of his personal assets.

Okada read over 300 space journal papers, contacted the paper authors, and flew to meet them in person to learn more. "Thinking back, I feel so embarrassed that I asked such basic and silly questions to these experts," he recalled.[50] As he learned more about the risks posed by debris and the existing policy responses, he formulated an explanation for the lack of progress:

> The ADR issue has been caught in a triangle of technological, legal, and financial challenges. Technology people say they cannot develop technologies without proper funding, legal people say they cannot design needed legal framework without knowing what kind of technologies are used for ADR. None would dare to pay for the costs of ADR unless some promising technologies are developed and necessary legal frameworks are in place.

Okada initially considered the possibility of a consulting or advocacy approach – to raise awareness of the issue and potentially advice a space agency how to proceed. However he quickly realized that this approach had been tried in the past with little success and hence decided to pursue a more entrepreneurial approach to solving the problem. If Astroscale could demonstrate that its technology was effective and could be provided at significantly lower cost than the current estimated ADR costs, Okada and his team might be able to break through the deadlocked triangle he observed.

As an entrepreneur actively working on an ADR solution, one option for Okada was to become a component manufacturer, where he focused his efforts on a key product that would become part of a larger solution. The other alternative was to develop a complete end-to-end service solution. His experience as an entrepreneur had taught him that small, component manufacturers typically had low margins and had to account for significant amounts of working capital stemming from the long delays in payment from larger industrial customers. He therefore decided to pursue the more risky, and more

capital intensive path of developing an end-to-end solution. Okada noted that "on our motorways there are rules to prevent accidents and services to help if your car breaks down. On the highway in space there are no rules, no policemen and nothing to help if your satellite breaks down, even though in time, space will be more congested." This led him to the vision of building the "*AAA* of Space."

Developing the Technology

Debris capture and deorbit technologies were divided into three categories: pull, push, and contactless. (See **Exhibit 7** for summary and examples of technology development options.) The pull approach was regarded as the most promising by experts. International space agencies actively studied pull technologies, including throw-nets (canister-ejected nets that wrapped around the target debris and tugged it to deorbit with a chaser weight), harpoons (tools that pierced the object and pulled it into deorbit similarly to the throw-net approach), and electrodynamic tethers (which generated electricity to slow the target debris and cause it to deorbit).[51]

Push technologies included tentacles and robotic arms that rendezvoused with the object in space. MIT's Saenz-Otero explained that using a robotic arm would reduce some of the complexities associated with interacting with an uncooperative space object: "The arm allows the servicing [or capture] satellite to not need to be perfectly aligned with the object. You can dock at any angle."[52] Contactless technologies, better suited for larger objects, included (1) ion beams using plasma to create a slowing force on the object and (2) particle clouds to slow or, according to Saenz-Otero, "ablate the object's speed by making it smash into a cloud of particles."[53]

By September, 2013, Okada had decided on a plan to develop an adhesive-based push approach. While adhesives had been the center of some research efforts, so far no space agency or company had adopted an adhesive that was proved successful in the space environment. Okada thought an adhesive could be just as effective but cheaper, lighter, and simpler than other capture technologies: "I was looking for the lightest and smallest approach. Mass has a direct impact on cost (development and launch cost). Pull strategies and some of the push strategies are all heavy (e.g., 100 kg), while adhesive is ultra light (e.g., 100 g). Debris shape and structure varies a lot; thus I was looking for capturing systems, which can be applied to various types of shapes and materials. I found adhesive is best." Astroscale partnered with a Japanese chemical company to develop the adhesive concept.

Okada set an aggressive timetable, internally referred to as "the 7 Year Marathon," to become the first private company to fully fund and test an ADR technology in space. Milestones were set for every two years to keep the company on target, with the first removal demonstration mission, ADRAS-1, planned to launch in the first half of 2018, just three years after initial concept design and much faster than standard development projects in the space industry. (See **Exhibit 8** for Astroscale's "7 Year Marathon" strategy.)

Financing and Team Building

Okada also needed to raise capital for his venture. He estimated the financing required to reach the milestones set in the "7 Year Marathon" would be about $100 million. In an effort to raise non-dilutive capital, he applied for and won a contract with a Japanese pharmaceutical company, Otsuka Pharmaceutical, creator of the sports drink brand Pocari Sweat, to design a lunar time capsule that would contain written messages from 100,000 children and be sent to the moon. Though the project was unrelated to space debris, it helped enhance Astroscale's visibility as a space company and kick-start initial funding for the company's ADR research and development through upfront milestone payments. "Having a solid and confirmed project can enable me to develop good relationships and also increase credibility . . . [as] someone who brings in real projects with real money," Okada said. "By

building this relationship, it became easier for me to bring in larger groups into debris removal projects."

By February 2015, Astroscale had raised $7.7 million in Series A funding from nine Japanese angel investors and a leading Japan-based venture firm, JAFCO Ventures, which also had a presence in Silicon Valley. He set a threshold investment of at least $500,000, so as to keep his syndicate of investors relatively small, but to also attract visionaries who would give him the flexibility to operate in a context where there was no existing market. The Series A capital raise had helped to finance a 325-square-meter manufacturing facility in Tokyo capable of developing three satellites simultaneously. The funding also served to attract what Okada called "Space Sweepers," a team of 20 space engineers, researchers, and physicists. The head of Astroscale's operation in Japan, a former researcher at the Japanese Aerospace Exploration Agency (JAXA), explained the reason why she joined Astroscale: "There are already companies which make satellites and provide services. I would not have been surprised if Astroscale's plan was just developing satellites. But when I heard that there was a company that wanted to clean up debris, I thought it was a big challenge and very impressive."[54] By 2016, Astroscale's workforce included 6 employees at the company's headquarters in Singapore and 14 based at the Tokyo manufacturing facility. Most hires came from universities, research institutes, and large Japanese companies. Those from academia were predominantly from the laboratories of professors from whom Okada had previously asked for feedback on his ideas. These individuals and laboratories officially became Astroscale's research partners.

By early 2016, the company was partnering with 46 members from nine universities, including 11 professors and 35 students. At this point, Astroscale had also applied for six separate patents. Okada felt the time was right to start the process to raise a Series B round of funding.

Initial Market Opportunities

The appeal of an ADR service provided to customers could take a variety of forms. Satellite operators would be interested in preserving their existing satellites in orbit. Similarly, companies planning to launch satellite constellations (hundreds or thousands of satellites forming a cohesive network) would require servicing or replacement of defunct satellites that must to be in precise fixed locations within the array. Okada saw a promising potential market his company could corner: "Suppose the failure rate in postmission disposal is 10%. If the satellite network provider launches 1,000 satellites, they'll have to follow emergency satellite removal procedures for at least dozens of satellites that go out of order. We call this retrieval service allowing satellite operators timely replenishment as End-of-Life (EOL) service. Unlike ADR service, EOL can be a commercial service with clear economic value proposition to satellite operators. (see **Exhibit 9** for comparison between EOL and ADR)".

OneWeb's founder, Greg Wyler, said, "On my tombstone, it should say 'Connected the world,' not 'Created orbital debris.'"[55] OneWeb had raised a $500 million Series A round of financing in June 2015 to support their efforts. SpaceX, Samsung, and Iridium Communications, all of which had announced constellation plans, would likely have the same concerns Wyler expressed. Philippe Moreels, Head of Strategy and Business Development at Astroscale noted that there were 20 announced plans of constellations, suggesting that in theory 15,000 satellites would be launched over the next 5-10 years. "Even if 20% of those forecasts are realized, this would still amount to 5,000 new satellites in LEO over the next few years just from such constellations", he noted.

Okada believed that if Astroscale could prove that it had a reliable and competitive EOL solution for private customers, international organizations such as IADC or the UN's COPUOS might mandate more stringent removal regulations rather than relying on mitigation attempts. This could generate

huge demand and foster ADR market growth. Okada said: "In recent years, the space industry has seen a shift from governments to the private sector as a consequence of shrinking budgets. Governments support and expect private companies to act as enablers in developing the next generation of technologies and spacecrafts using disruptive processes and with cost-effectiveness."

Okada calculated that Astroscale's adhesive push technology coupled with the satellite configuration could cost less than one-tenth of the cost of other ADR technologies, which were estimated at $100 to $500 million for each debris removal mission.[56] Perhaps Astroscale's solution could provide the kick start governments needed.

Moreels outlined four areas of focus for Astroscale as articulated to potential investors (see **Exhibit 10)**. First, Astroscale was focused on developing "Space Situational Awareness" products in terms of small-sized Debris Monitoring. He noted that "most LEO satellites are injected into Sun-synchronous orbit where the sun can power them at altitudes ranging from 700-900 km - adding to congestion in space. Space debris above 10 cm can currently be tracked from the ground and the threshold is meant to become lower - to 5cm - over the upcoming years thanks to technological advances. However, even debris with a 2 cm diameter can completely destroy a satellite. We currently lack a good understanding of these smaller debris and Astroscale could help map the space environment and sell the resulting data to those interested in protecting their assets." For example, the company AGI, provides commercial satellite operators and government space centers real time data on space objects, through its Commercial Space Operations Center (ComSpOC). They and others like them could be customers of the smaller debris mapped by Astroscale. Astroscale was not the only venture looking at debris monitoring; a prominent competitor in this space was another startup, Leolabs, which was focused on mapping debris 2 cm. and larger.

A second area of focus was Debris Mitigation, by helping satellite operators effectively dispose satellites once they had reached end of operational lifetime. Astroscale's efforts in this realm involved the demonstration of a sail that could be deployed to increase atmospheric drag and push satellites down faster. Key to such debris mitigation services was the weight of the add-on to the satellite - since these not only impacted launch costs, but more importantly could shorten the useful life of satellites due to their greater need for power. A key potential competitor in this realm was D-Orbit, an Italian startup founded in 2011. Okada believed however that Astroscale's solution, if successful, would be more cost-effective due to its light weight relative to other options being planned by competitors. He noted, however, that a limitation of the sail was that it was only effective at lower altitudes – below 750 Km – and that D-orbit would be complementary for satellites requiring autonomous boosters (that is, those above 750 Km but below GEO (36,000 Km.)

Third, Astroscale hoped to develop a business in "Space Traffic Management", where they could help customers anticipate and avoid collisions with debris capable of causing catastrophic damage. Moreover, space traffic management would arise as a natural consequence if governments could be persuaded to monitor and regulate space in a manner similar to earth. This was particularly important given the fact that ADR had the potential to become a national security concern: using ADR, it was possible for one company or nation state to de-orbit active satellites belonging to someone else, or to contract with a private firm to do so. "Being neutral is very important for us", noted Okada, who also felt that being located in Singapore was an important source of competitive advantage for Astroscale.

Lastly, Moreels noted that Astroscale was focused on developing a business around EOL, in-orbit servicing for satellites and ADR. Okada noted that the first two areas of focus could be sold as a service to satellite companies. Okada believed that in particular, communications satellites would have a higher willingness to pay, given their need to have *all* their satellites up and running in order to provide adequate service to customers. (see **Exhibit 11** for details on financials of some publicly traded Satellite

companies). He also projected that launch costs for Astroscale would fall further from the current $20-$50 million to under $5 million over the upcoming few years, making EOL, ADR, and in-orbit servicing economically make sense for satellite companies to keep their business sustainable.

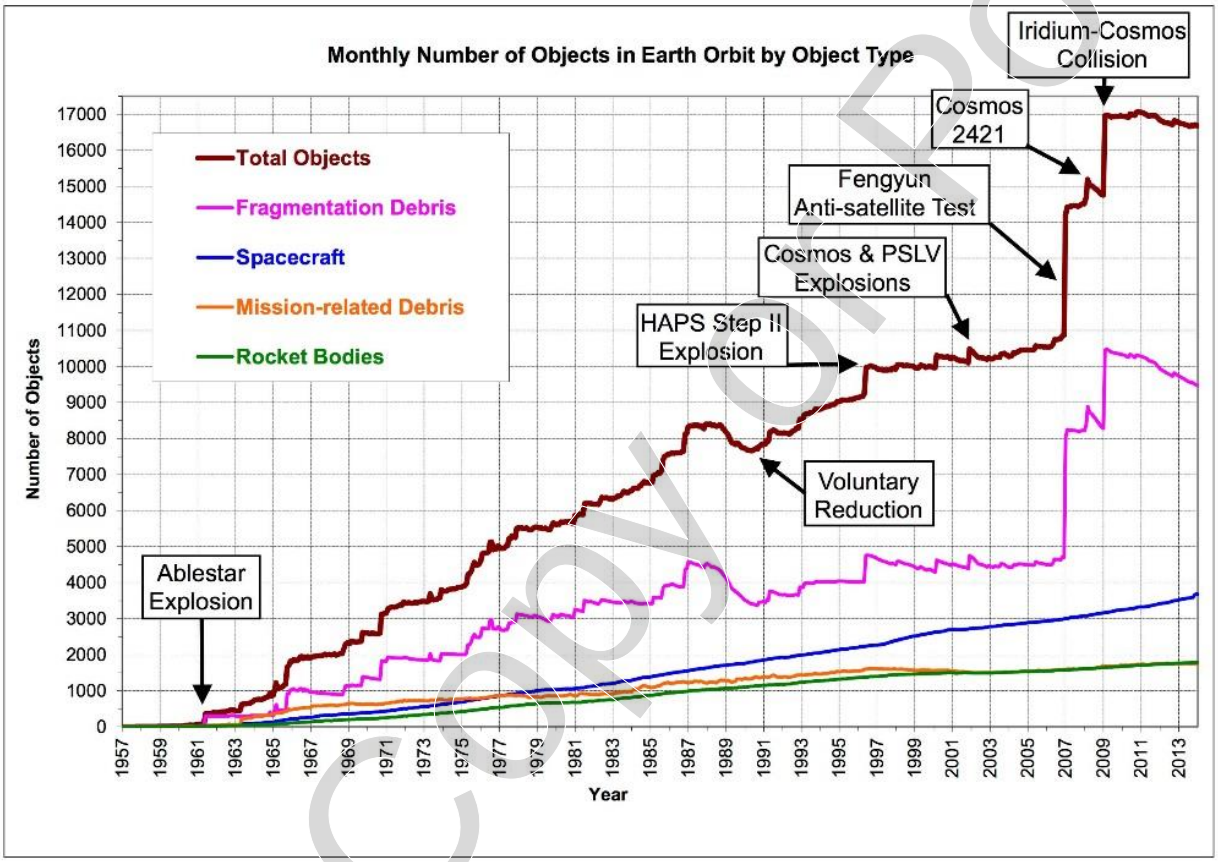
Series B Financing

Nobu Okada's Astroscale was attempting to enter an environment dominated by powerful players—incumbent industry mammoths, civilian space agencies, and military organizations—with massive budgets in comparison. "How do we crack the rock? It's a big rock and we only have a small wedge," Okada mused.

But Okada believed that he was tackling an important challenge:

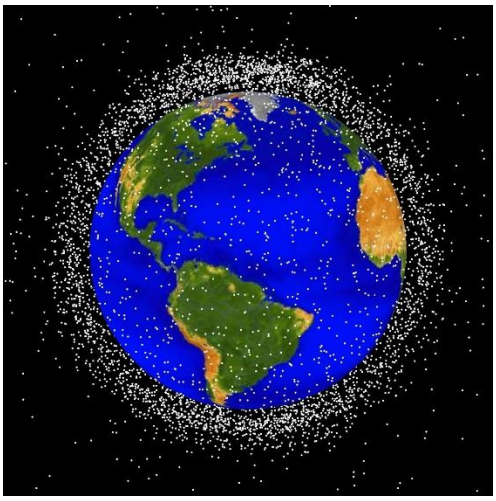
> There are many issues to be solved in society, and I think some are more difficult to solve than others. Issues resulting from market failures are more difficult to solve than issues resulting from failure of capturing changes in the market. And issues caused by the tragedy of the commons are the most difficult to solve.
>
> I believe that this is the right time for the private sector to pave the way to create an international standard to redefine and shape the way space users have been dealing with space-use in the past. Although the dream of an international standard is far in the future, we at Astroscale are optimistic that we can accelerate that process through business creation from the private-sector viewpoint.

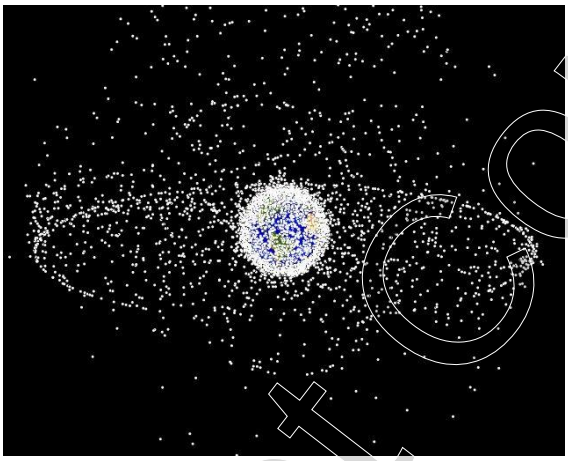
Exhibit 1 Number and Type of Objects in LEO over Time



Source: NASA Orbital Debris Program Office.

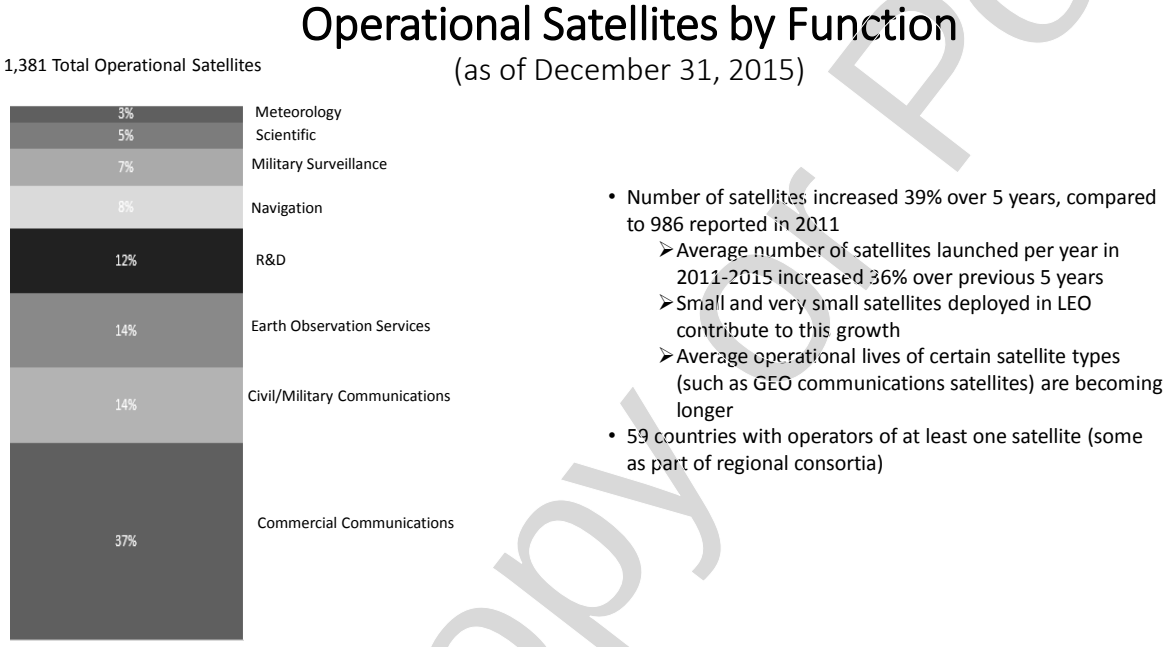
Exhibit 2 Illustration of Objects in LEO and GEO





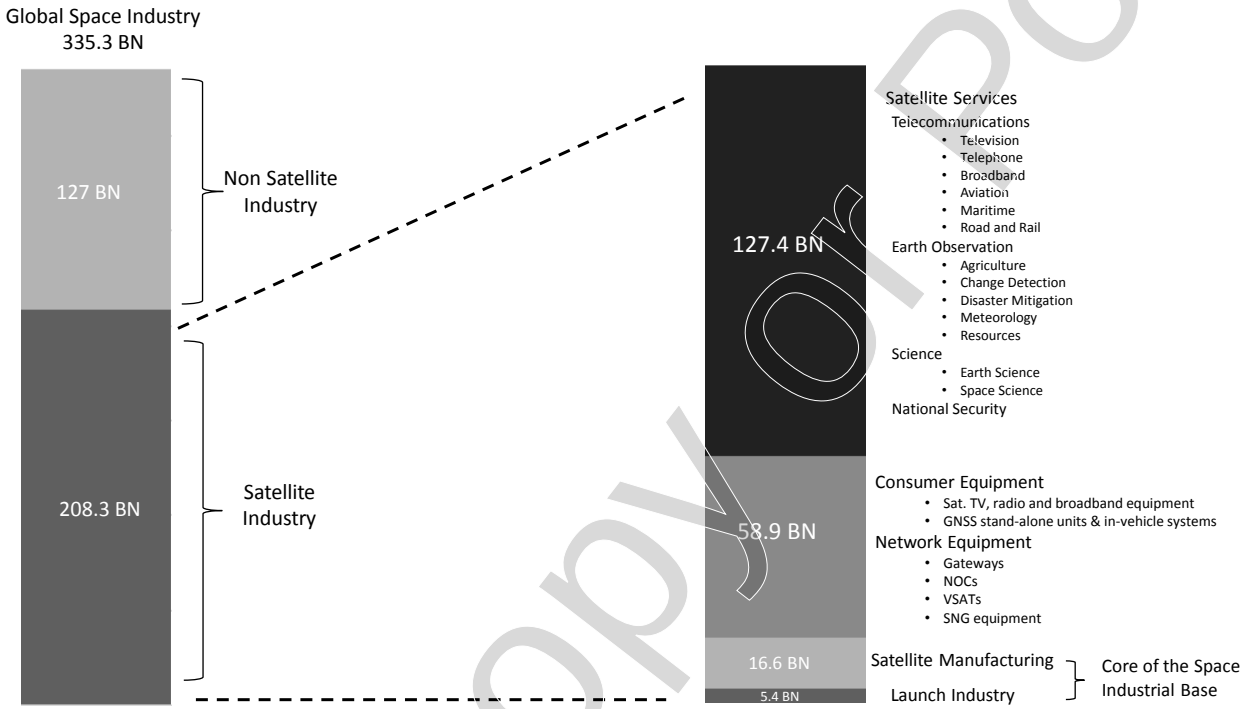
Source: NASA Orbital Debris Program Office.

Exhibit 3 2015 Space Industry Revenue breakdown



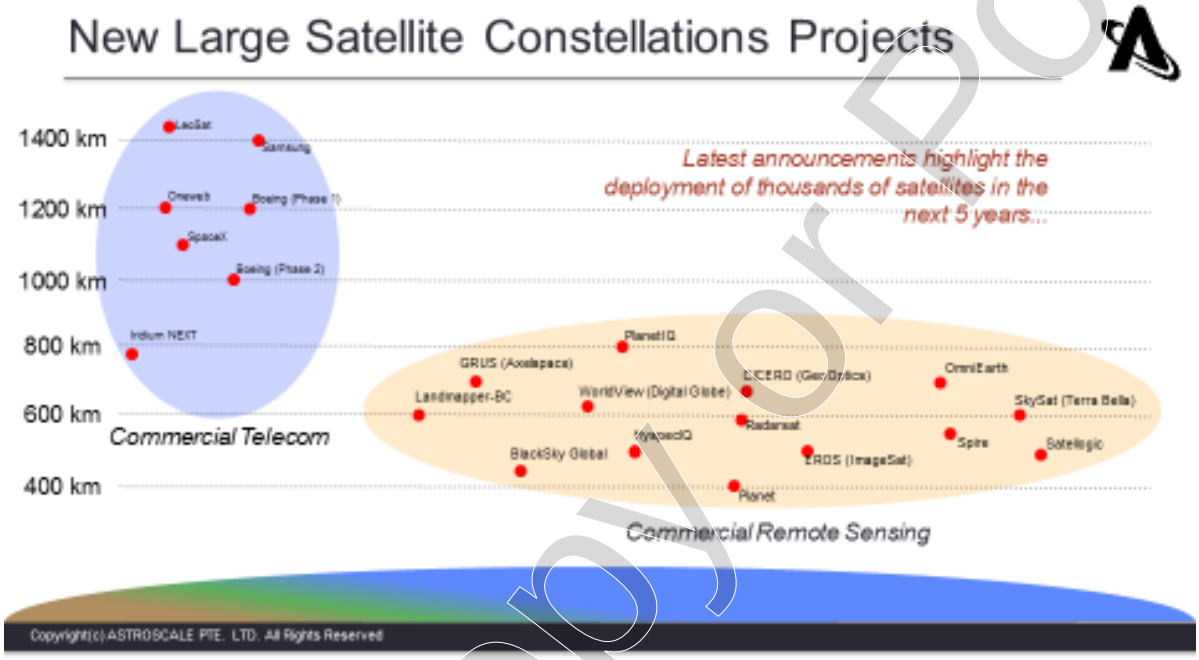
Source: Adapted from Satellite Industry Association, *State of the Satellite Industry Report,* September 2016, http://www.sia.org/wp-content/uploads/2015/06/Mktg15-SSIR-2015-FINAL-Compressed.pdf, accessed November 2016.

Exhibit 4 Satellite Industry Revenue Breakdown



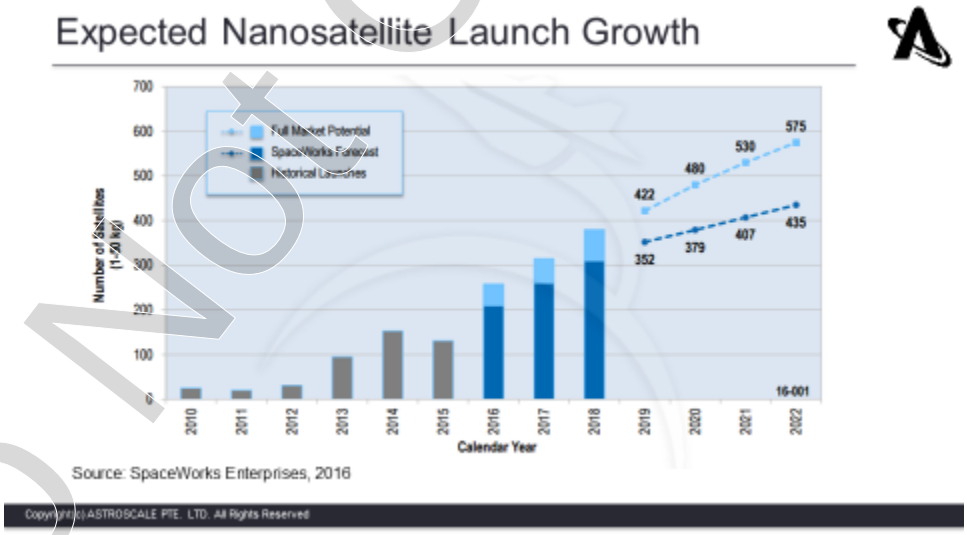
Source: Adapted from Satellite Industry Association, *State of the Satellite Industry Report,* September 2016, http://www.sia.org/wp-content/uploads/2015/06/Mktg15-SSIR-2015-FINAL-Compressed.pdf, accessed November 2016.

Exhibit 5 Satellite Constellation Projects



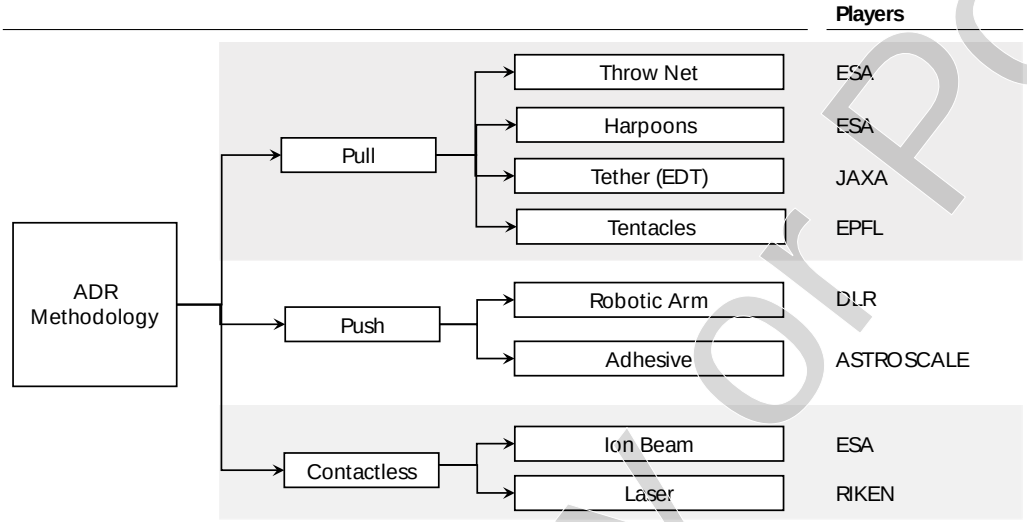
Source: Company documents.

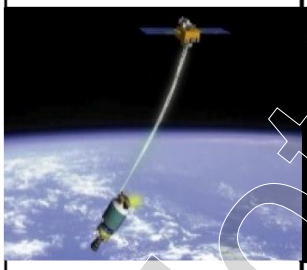
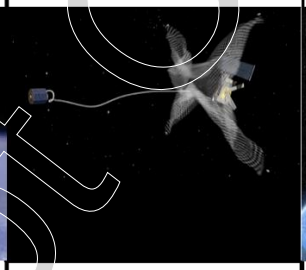
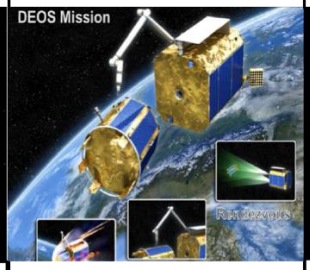
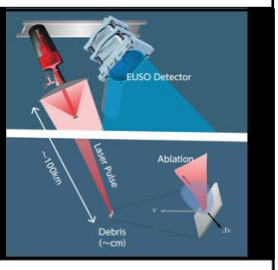
Exhibit 6 Projected number of launches of 1-50 Kilogram Satellites



Source: Company documents.

Exhibit 7 Examples of Deorbiting Technologies

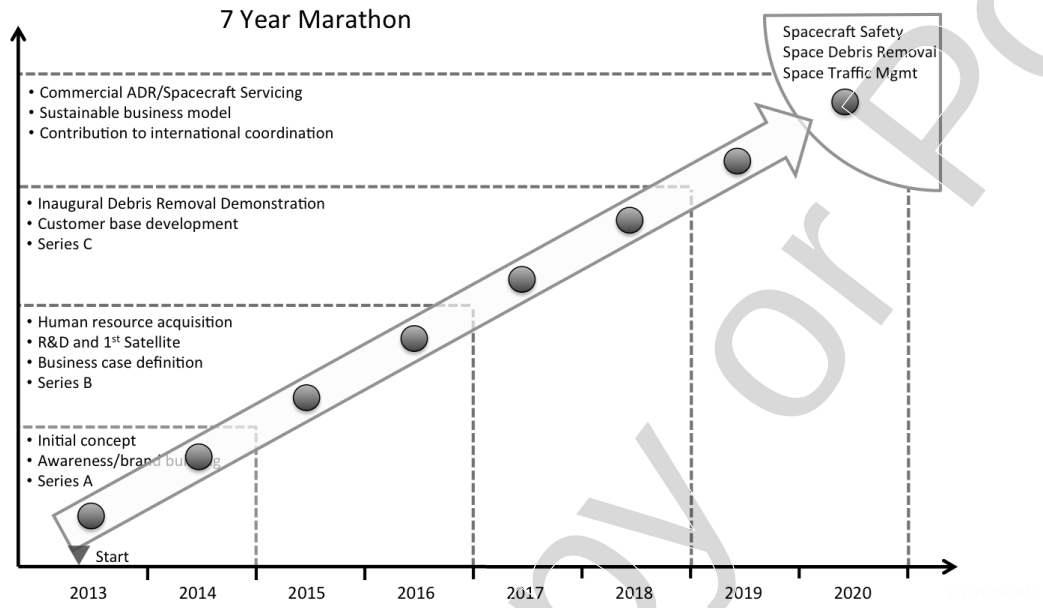


Space Agencies (Examples)			Non-space agencies
Japan/JAXA	Europe/ESA	Europe/DLR	Riken
PULL	PULL	PUSH	CONTACTLESS
			
An electrodynamic tether (EDT) is designed to generate electricity that will slow down space-based debris. The slowed-down space debris will fall into lower and lower orbits until burning up in Earth's atmosphere	A catcher satellite shoots out a weighted net on the end of a tether. The net spreads as the weights fan out, then engulfs the target as the tether pulls tight.	Catch the debris using robotic arms. Planned mission include refueling and installing new M&E equipment DLR plans to use the results for future OOS and ADR technology development	Riken develops a plan to dock a laser onto the ISS (International Space Station) to sweep away debris

Source: Company documents.

Note: ESA (European Space Agency); JAXA (Japanese Exploration Agency); EPFL (Swiss Federal Institute of Technology); DLR (German Space Agency); RIKEN (private Japanese research center).

Exhibit 8 Astroscale's 7 Year Marathon strategy



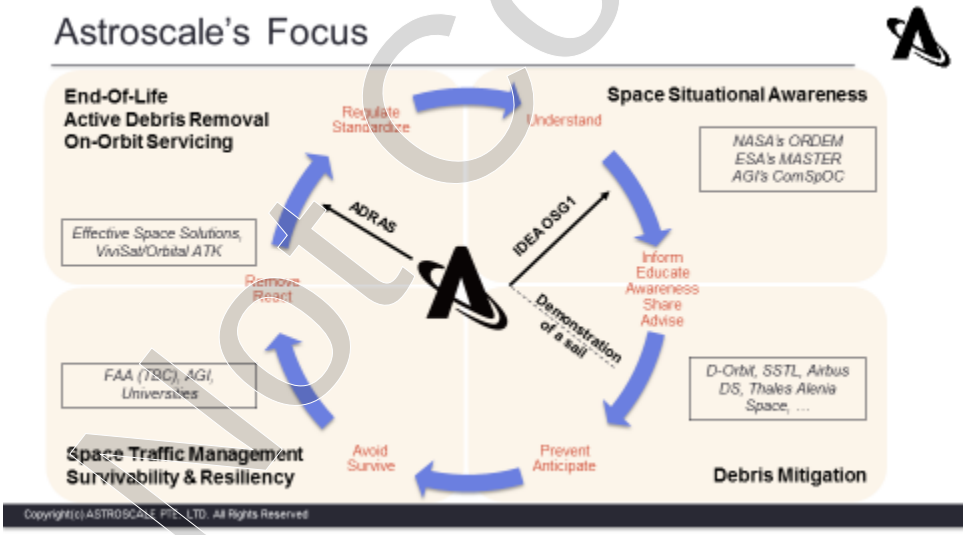
Source: Company documents.

Exhibit 9 EOL vs ADR

	End-of-Life service	Active Debris Removal
Target objects	Satellites reaching end of operational lifetime	Environment Critical Objects
Mass	50kg ~ 500kg	500kg +
Rationale	Retrieve satellites allowing timely replenishment operations	Remove space debris to improve safety and risks of collisions
Key Technologies	Semi-Collaborative approach and capture	Non-collaborative approach and capture
Value proposition	Operational Orbit sustainability Maximize revenue Mitigate Collision Risk	Long-Term sustainability
Regulations/ Authorization	B2B Commercial contract following mission approval from launching State	Requires International consensus

Source: Company documents.

Exhibit 10 Astroscale's four areas of focus



Source: Company documents.

Exhibit 11 Financials for select, publicly traded, Satellite Operators

	Intelsat	Digital Globe	Iridium
Revenue	2,472	654	409
Operating Income (EBIT)	1,247	32	123
Net Fixed Assets	5,880	2,175	1,972
Capex	645	234	441
Depreciation and Amortization	679	240	72
Net Working Capital	(247)	(279)	(12)
EBIT / Revenue	50%	5%	30%
Net Fixed Assets / Revenue	238%	333%	482%
Net Working Capital /Revenue	-10%	-43%	-3%

Source: Compiled from Capital IQ, and casewriter calculations.

Note: None of the Mega Satellite Constellations that would be target customers of Astroscale have publicly available data. It is conceivable that they may have somewhat different operating metrics.

Endnotes

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