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Astroscale, Space Debris, and Earth's Orbital Commons

Despite extensive tracking networks put in place by international space agencies, nobody seemed to notice the two satellites hurtling toward each other at 22,300 mph just 500 miles above the Earth. 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. By 2015, these and many smaller incidents had left 23,000 trackable objects, an estimated 500,000 particles between 1 and 10 cm, and over 100 million particles smaller than 1 cm in Low Earth Orbit (LEO), according to the U.S. Space Surveillance Network (SSN).[1] (See **Exhibits 1** and **2** for number and class of objects in space.)

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.[2] Exploding grenades in LEO was a risky proposition, as modern society depended on satellites in that region of space for telecommunications, geopositioning, weather forecasting, banking, and other services. 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."[3]

Officials responsible for mitigating the threat from space debris expressed a mixture of urgency and caution. 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."[4] 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

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so—10 or 20 years, maybe."[5] In fact, NASA announced in 2014 that it would not pay for in-flight demonstrations of active debris removal (ADR) technologies.[6]

Nobu Okada, a Japanese information technology (IT) entrepreneur and former strategy consultant, saw a business opportunity in this mixture of urgency and caution. After receiving his MBA from Purdue University as part of an exchange program while working for Japan's Ministry of Finance, Okada founded a string of IT start-ups. "I attended some space conferences when I was in the information technology industry," Okada recalled. "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?' The big moment for me occurred at a meeting in Germany in April 2013. All the debris professionals were gathered together, around 300 people. They were still talking about whether technology comes first or funding comes first or regulation comes first. I was frustrated but also quite excited at that moment. I had found an opportunity because nobody had a clear idea how to solve the problem."[7]

In 2013, Okada founded Astroscale, using half of his personal fortune as seed money. Over the next two years, Okada hired a team in Tokyo and Singapore, raised capital, and partnered with a Japanese chemical company to develop an innovative adhesive-based approach to 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. (See **Exhibit 3** for satellite concept designs and debris targets.) Okada also attempted to raise public awareness of the threat from space debris, which he saw as a prerequisite to government action.

On the one hand, 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 in, as the Japanese proverb put it, "trying to crack a large rock with a small wedge"? How?

On the other hand, a wide range of experts seemed to agree that space debris would eventually require a solution, and developing that solution would take time. 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.' That is, the amount of debris—in terms of the population of large debris objects, as well as overall mass of debris in orbit—currently in orbit has reached a threshold where it will continually collide with itself, further increasing the population of orbital debris."[8] According to Donald Kessler himself, "The cascade is happening right now [2013]—the Kosmos-Iridium collision was the start of the process. It has already begun."[9]

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,"[10] 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 6,000 satellites into orbit,[11] of which 1,261 remained operational by the end of 2014.[12] But projections suggested that the number of satellites was about to grow dramatically. 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.[13] SpaceX, a private rocket and spacecraft manufacturer and launch company, had secured $1 billion in January 2015 to launch 4,000 satellites.[14] And Samsung, a Korean technology conglomerate, was reported to be developing a 4,600-satellite network.

The proliferation of satellites 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.[15] 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."[16]

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 scientific research sectors being driven by the so-called New Space sector.[a] 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.[17]

Tragedy of the Orbital Commons

By the 2010s, Earth's orbital space had become described in the aerospace sector as "congested, contested, and competitive."[18] As space debris accumulated, the risks posed to public and commercial space activities and the global economy intensified. But those risks were spread widely and provided weak, if any, incentive to individual actors to limit the production of debris or the risk of collisions.

This situation—in which private actions reduced the value of a common resource beyond the private cost such actions entailed—was dubbed the "tragedy of the commons" by social scientists.[19] Though originally developed in the context of crowded cattle pastures in England, this idea's applicability apparently extended even to the vast scale of Earth's orbital space.

If a global government had existed, it could have imposed taxes or regulation to "internalize" the externality that private actions were imposing on others in space—that is, to make the private costs of

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[a] See Matthew Weinzierl and Angela Acocella, "Blue Origin, NASA, and New Space (A)," HBS 716-012 (Boston: Harvard Business School Publishing, 2016), for a discussion of the New Space sector and its rise.

producing space debris equal to the overall costs to society. Without such a government, however, countries and companies would have to find another way.

Property Rights and the Coase Theorem

Economist and Nobel Prize laureate Ronald Coase argued that negotiations among interested parties, if the costs of bargaining were low and property rights were clear, could solve the tragedy of the commons without direct government intervention. According to what became known as the Coase Theorem, such negotiations would assign a price to the costs that private actors otherwise could ignore, leading to an outcome with the efficient level of activity—that is, the level at which the total cost to society of the last unit of activity equaled its benefit.

In some ways, the space debris challenge seemed ripe for a Coasian solution. After all, a relatively small number of large communications companies, satellite and launch providers, and space agencies, especially those tied to national defense, had considerable incentives to ensure a secure space environment. (See **Exhibit 4** for satellite industry breakdown.) Moreover, the costs of a catastrophic Kessler Syndrome would be felt most directly by these few players, whose businesses (or national security apparatuses) depended on LEO satellites.

The problem, however, was property rights. Economist Alexander Salter put it succinctly: "[T]hat which nobody owns, nobody will care for."[20] International law forbade the allocation of property rights in space, rendering space *res extra commercium*—an area independent of commercial activities, to be used but not appropriated. In particular, the 104 signatories of the 1967 Outer Space Treaty (OST), including the U.S., China, and Russia, agreed to the following statement: "The exploration and use of outer space, including the moon and other celestial bodies, shall be carried out for the benefit and in the interests of all countries, irrespective of their degree of economic or scientific development, and shall be the province of all mankind."[21] In principle, this agreement gave property rights to space to every human. In practice, such a diffuse property right had much the same effect as no property rights at all.

One possible solution came from the fact that the OST did define ownership rights for objects placed in space: "A State Party . . . shall retain jurisdiction and control over such object [launched] . . . while in outer space or on a celestial body."[22] Moreover, nations would be responsible for the actions of their nongovernmental entities, including private organizations. If a country was responsible for the effects of its space debris, perhaps the tragedy of the orbital commons could be avoided after all.

Ironically, however, the OST directive on ownership of space objects also put in place an obstacle to progress. It stated that ownership of "component parts" (i.e., debris) remained with the original owner, so salvage of an object could be done only by or with permission of the original owner. This statute threatened to pose legal barriers to future ADR activities, as determining the ownership of many debris objects was difficult, especially since actors were hesitant to acknowledge ownership and accept the liability doing so entailed.[23]

International attempts to adopt more stringent limits on activities in space, and thereby limit the risk of the tragedy of the orbital common, failed in the face of the vast possibilities for economic and scientific gain. The 1979 Moon Treaty defined "the moon and its natural resources as the common heritage of mankind," but it was ratified by only a handful of non-spacefaring nations.[24]

Elinor Ostrom's Polycentric Governance

A second Nobel Prize–winning political economist, Elinor Ostrom, argued for another solution to the tragedy of the commons, sidestepping the need for clear property rights. Through careful research on how societies had historically solved such problems, Ostrom identified what she called "polycentric governance" as a promising approach. The idea was that interested parties were not necessarily the narrowly self-interested, myopic actors assumed in a classic tragedy of the commons. Instead, parties could be encouraged to adopt nonmarket rules and institutions that ensured sustainable, shared, and economically efficient resource management.[25] Though related to Coase's idea of efficient negotiation, Ostrom's approach could work (in principle) even if the parties were national governments or private firms across which property rights in space were unspecified. Perhaps, then, actors with the greatest stakes in space could follow this approach and create collective norms for debris mitigation and removal without a global government.

To validate her theory, Ostrom conducted extensive field studies. From these studies, she derived a framework to better explain solutions to shared resource issues through informal coordination between individual participants.

In one such study focusing on global forest protection where rural communities depended on the ecosystem of the local forests, Ostrom and colleagues found that some locally managed forests thrived and promoted reforestation efforts better than government-protected forests. A comparison of three Indian forest management regimes—community initiated, nongovernmental organization (NGO) promoted, and state sponsored—showed that the local enforcement of forest monitoring was more effective for forest regeneration and for prevention of grazing and fire than state-led initiatives, and that NGO-promoted forest monitoring focused too heavily on protection of resources from outsiders rather than on prevention of resource overuse and depletion by local actors.

Local forest conservation movements came about when the felling of trees by members from within the community and from neighboring villages resulted in forest health degradation, limits on water availability, and loss of employment opportunities for forest-dependent harvesting industries. The local community responded by establishing rules to limit the quantity and species of timber each household could harvest. Daytime patrol by community members (one male and one female selected from two separate households, on a rotational basis) was set up to enforce these rules; compliance was monitored; and sanctions for rule breaking, including a graduated penalty structure with increasing punishment severity for repeat offenses, were enforced informally without legal authority.[26] This study demonstrated that, contrary to the conventional theory of collective action, efficient allocation of common resources could be established through cooperative measures among local actors, absent private property rights or government intervention.

Another such study investigated water irrigation systems in Nepal, wherein farmers constructed and maintained many of the systems, while the rest were built and managed by the government. Local farmers managed their irrigation systems through annual meetings and frequent informal interactions. Rules that fit the specific needs of the community could be established, such as those stipulating that all farmers using the system must contribute one laborer annually for the extensive maintenance the systems required. Water allocations were agreed upon at general meetings, and farmers could sell any unused water allowance, creating incentives for efficient water use. Penalties for nonconforming actors tended to be particularly severe, often involving physical punishment. Although harsh, sanctions were collectively agreed upon and adhered to.[27] Locally governed irrigation systems outperformed government-managed systems on overall measures, and in particular on physical condition, water quality, and agricultural productivity for the farms they served.[28]

Polycentric governance was not, however, simple to achieve. To succeed, it required a set of interested parties; the boundaries of their common resource; and clarity from the institutions of collective decision-making, monitoring, sanctioning, and dispute resolution. The international treaties on activities in space were light-years away from having clarified these points.[29]

Despite the challenges, some attempts were clearly being made to start building polycentric governance institutions for space debris removal, especially through intergovernmental cooperation. The main focus of these efforts had been mitigating the growth and threats from debris.

Debris Mitigation

Efforts to solve the tragedy of the orbital commons focused, in the late 20th and early 21st centuries, on not making the problem worse. That is, 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 norms 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.[30] 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.[31] 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.[32]

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.[33,34,35]

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.[36] 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.[37]

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.[38] 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."[39]

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. He went on:

> The "no new launches" assumption adopted for this study is, of course, not practical. . . . In reality, the LEO population growth will be greater than that shown . . . as spacecraft and their orbital stages continue to be launched into space. . . . [Mitigation] measures will be insufficient to constrain the Earth satellite population. Only remediation of the near-Earth environment, i.e. removing existing large and massive objects from orbit, will likely prevent the undesirable effects predicted.[40]

Liou was not alone in his judgment. Findings from a simulation of the LEO debris environment by the IACD 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.[41]

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.[42]

Challenges to Progress on ADR

Despite the seeming momentum toward ADR, actual investments in the technology remained muted. A number of challenges appeared to be preventing progress.

Lack of public pressure 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."

Technological barriers 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."[43] Liou himself noted, "As of today, there is no economically viable and technically feasible method to allow us to do it."[44] 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."[45]

Among the many technological obstacles to ADR, securing an uncooperative, spinning target traveling at over 17,000 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."[46] Space agencies, academic research institutes, and private companies tested various capture technologies, but their development efforts had so far resulted in few promising options.

Geopolitics 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.[47] Countries were reluctant to facilitate cooperation on ADR if it would mean sharing sensitive security information.

Financing Financing challenges also played an important role. "The stumbling block isn't the technology, the stumbling block is who's gonna pay?" said Harvard astrophysicist Martin Elvis.[48] Hugh Lewis, developer of the Debris Analysis and Monitoring Architecture to the Geosynchronous Environment (DAMAGE) space debris model, said, "It is very difficult to make a business case for this type of activity. The costs are high, as are the challenges, so who will pay?"[49]

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. "We would be totally stupid to be the only ones," outgoing ESA head Jean-Jacques Dordain said. "[O]ther space powers, including nations that put more objects into space than Europe, continue to disregard the debris issue."[50] Still, the main spacefaring countries felt that their investments and activities had benefited humankind around the world and that therefore debris removal cost burdens should be shared. This sentiment surfaced particularly in the wake of the Iridium-Kosmos collision. Russia claimed it was not responsible for the defunct satellite and was therefore not financially liable.[51]

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."[52] "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.[53]

Along with Astroscale, firms such as Tethers Unlimited, Star Technology and Research (STAR), and Australia-based Saber Astronautics had proposed various ADR technologies.[54,55,56] "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.[57] 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."[58]

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.[59]

Legal Finally, 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?[60]

Inevitable Tragedy?

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.[61]

Astroscale's Solution

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."[62] 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 the MBA program at Purdue University, which helped foster his entrepreneurial spirit. In the midst of the growing IT bubble, 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 IT company, which developed and provided smartphone applications in Singapore in 2009. 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.[63]

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. 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 began with the basics, and a Google search of "satellite development." He 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.[64] 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 thought he saw a path to resolving this stalemate. 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.

Innovation as the Solution

Debris capture and deorbit technologies were divided into three categories: pull, push, and contactless. (See **Exhibit 5** 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).[65]

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."[66]

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."[67]

By June, 2013, Okada had decided on a plan to develop an adhesive-based push approach and to concentrate on light debris in higher LEO orbits and heavier objects in lower LEO orbits. Okada and his team categorized the debris as one of two types: Zone 1 and Zone 2. (See **Exhibit 6** for Astroscale's target debris categories.) 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., 10 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 7** for Astroscale's "7 Year Marathon" strategy.)

Financing and Team Building

Okada also needed to raise capital for his venture. He won a contract for a sponsored mission 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 1 million 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. (See **Exhibit 8** for the lunar capsule concept design.) "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 investors and a leading Japanese venture capital firm, helping 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."[68] 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 and was planning to begin Series B 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." OneWeb's founder, Greg Wyler, said, "On my tombstone, it should say 'Connected the world,' not 'Created orbital debris.'"[69] SpaceX, Samsung, and Iridium Communications, all of which had announced constellation plans, would likely have the same concerns Wyler expressed.

Okada believed that if Astroscale could prove that it had a reliable and competitive ADR 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 about one-tenth of the cost of other ADR technologies, which were estimated at $100 to $500 million for each debris removal mission.[70] Perhaps Astroscale's solution could provide the kick start governments needed.

Enhancing Awareness

Okada believed a key to Astroscale's success would be to build public pressure for progress on ADR and to link Astroscale's brand with space debris solutions and long-term sustainability. Inspired by the "bottom-up" campaigns that had become popular grassroots initiatives addressing climate change as a result of Al Gore's 2006 documentary, *An Inconvenient Truth,* Okada thought a similar bottom-up movement could generate international community engagement around space debris. He began speaking at conferences and symposiums, including TEDx Tokyo in 2014, and in media around the world. "These days," said Okada, "I usually give talks once every two weeks somewhere across the globe: the U.S., China, Europe, Russia, Japan, Singapore." The company also sponsored events raising awareness among the general public and children, to help inspire them as Okada had been inspired in his youth.

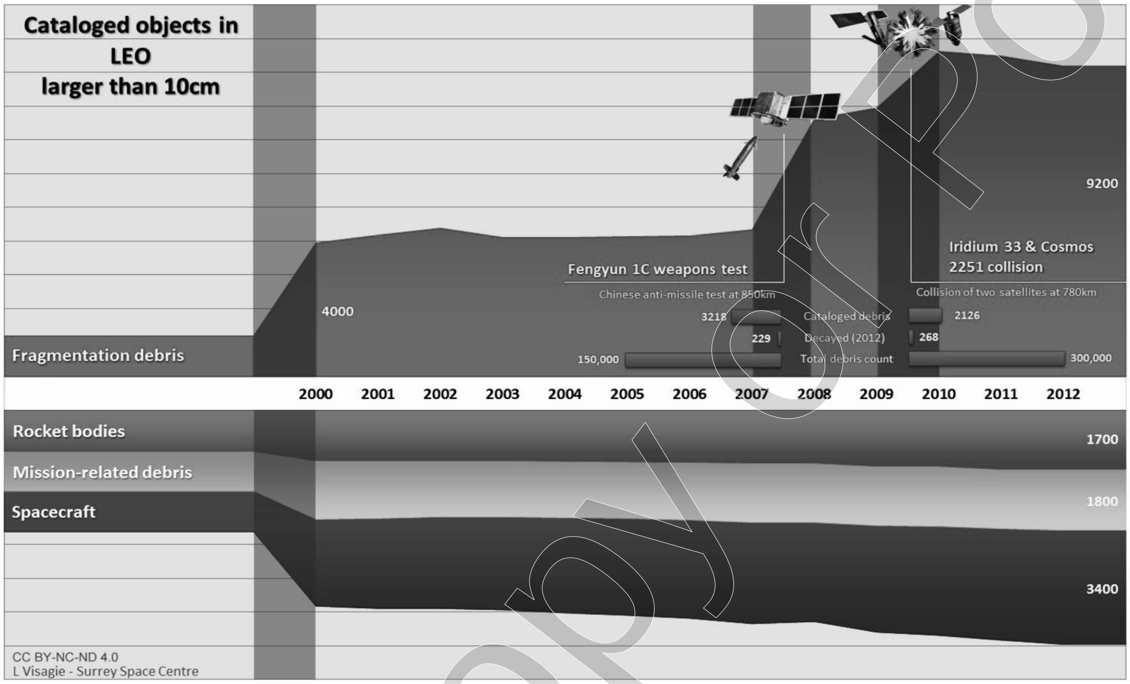
Cracking a Rock?

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:

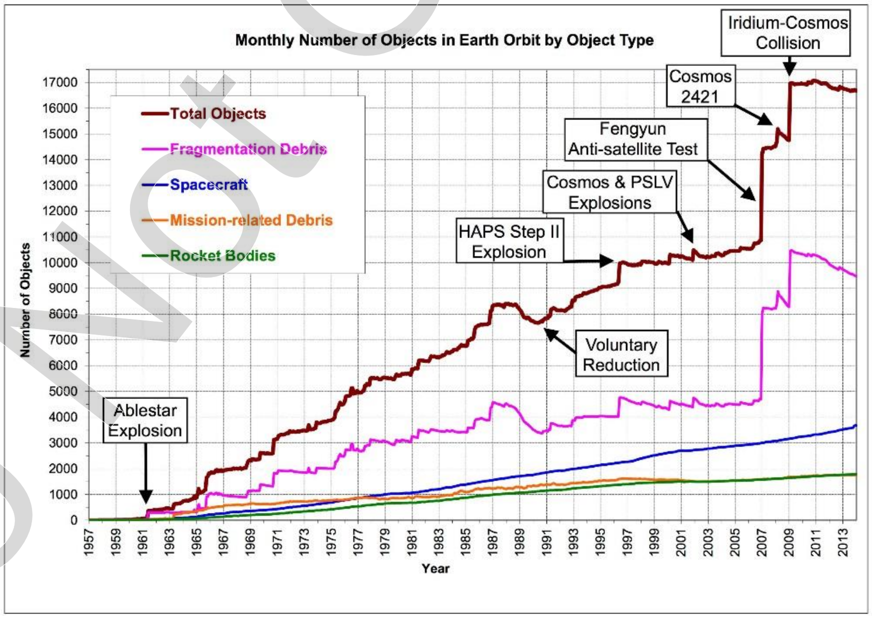
> There are many issues to be solved in society, and I think some are more difficult to solve than others. Issues resulting from market failures are more difficult to solve than issues resulting from failure of capturing changes in the market. And issues caused by the tragedy of the commons are the most 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



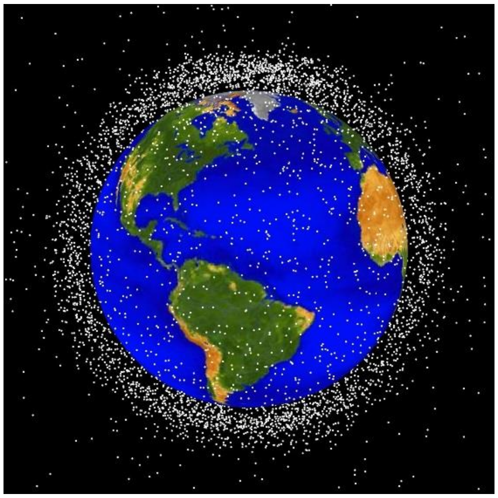
Source: NASA.

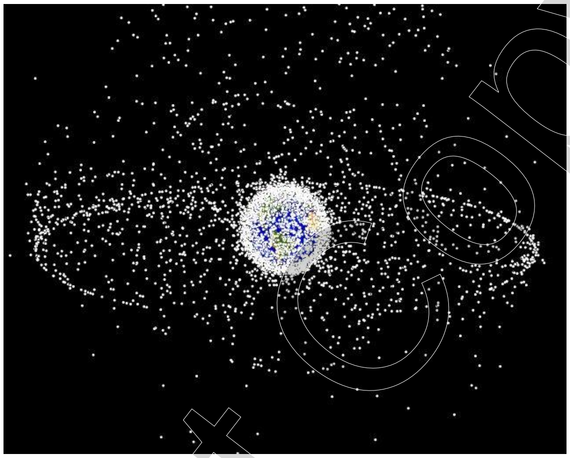
Note: Spacecraft category includes active and inactive satellites.



Source: NASA Orbital Debris Program Office.

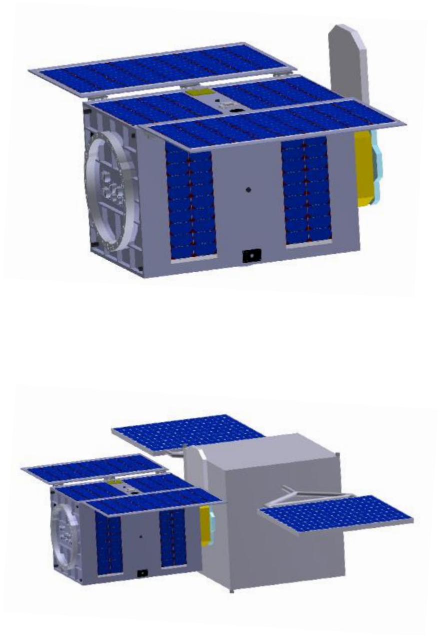
Exhibit 2 Illustration of Objects in LEO and GEO





Source: NASA Orbital Debris Program Office.

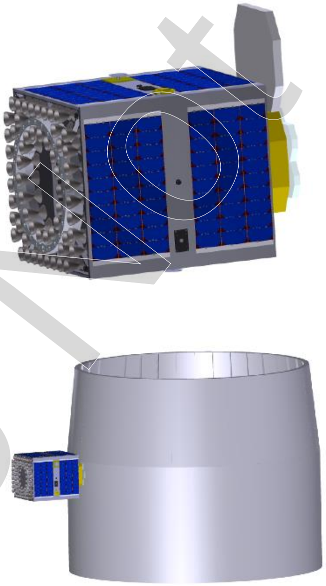
Exhibit 3a ADRAS-ION Adhesive Satellite System with Electronic Propulsion Capturing Light, High-Altitude (Zone 1) Space Object



Size	600 mm x 600 mm x 1000 mm
Mass	80 kg
Attitude determination	GPS, Star tracker, Sun sensor, Magnetic sensor, Gyro sensor, Acceleration sensor
Actuator	Magnetic torquer Reaction Wheel
Communications	S-band, X-band
Power supply	2 solar array paddles and body mounted solar array panels at 6 dimensions
Propulsion System	Electronic propulsion thruster H2O2 propellant thruster
Mission Module	Optical camera, Stellar compass, Infrared camera, Long range radar

Source: Company.

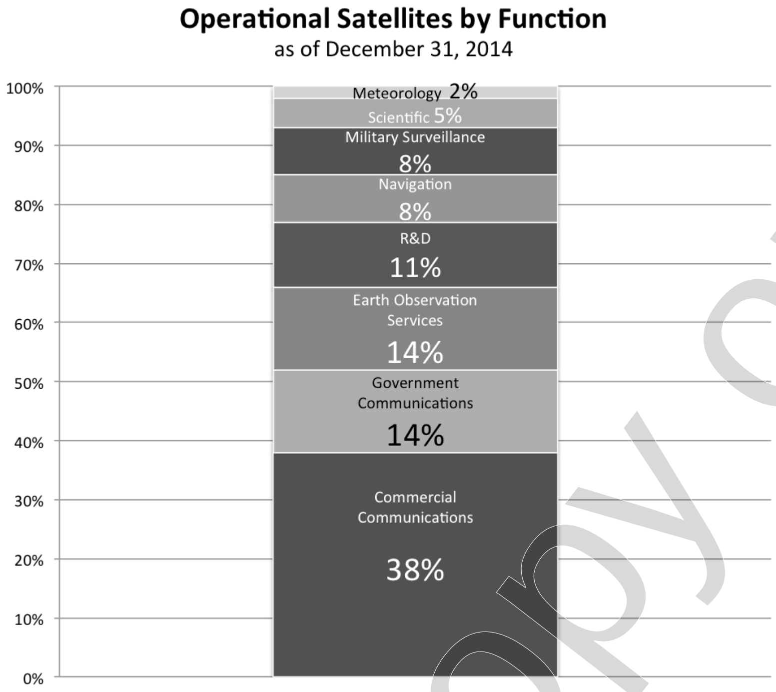
Exhibit 3b ADRAS-SRB Adhesive Satellite System with Solid Rocket Booster Capturing Heavy, Low-Altitude (Zone 2) Space Object



Size	600 mm x 600 mm x 1000 mm
Mass	80 kg
Attitude determination	GPS, Star tracker, Sun sensor, Magnetic sensor, Gyro sensor, Acceleration sensor
Actuator	Magnetic torquer Reaction Wheel
Communications	S-band, X-band
Power supply	Body mounted solar array panels at 6 dimensions
Propulsion System	Solid propellant H2O2 propellant thruster
Mission Module	Optical camera, Stellar compass, Infrared camera, Long range radar

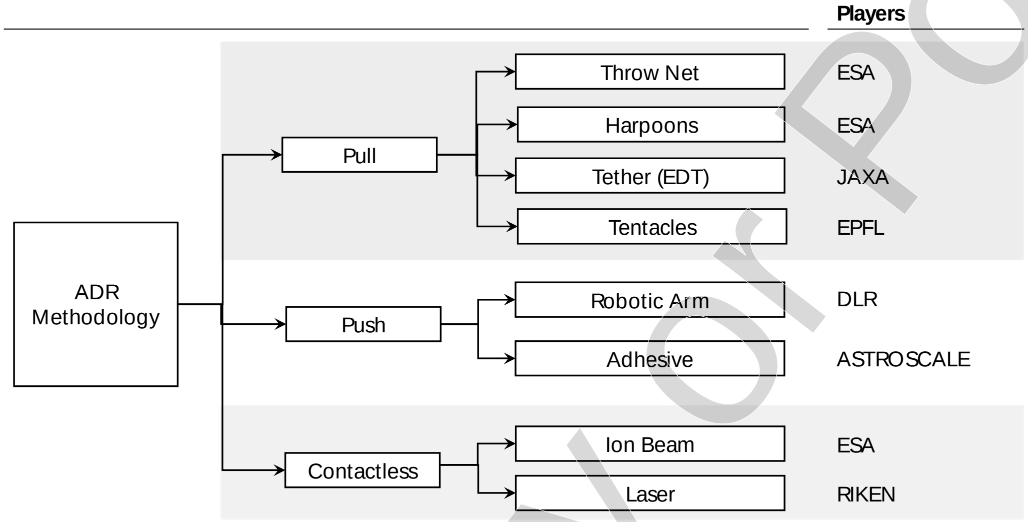
Source: Company.

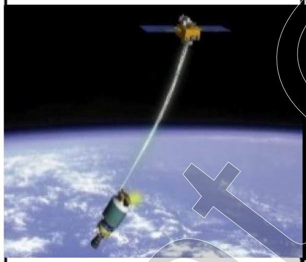
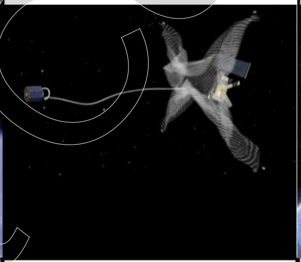
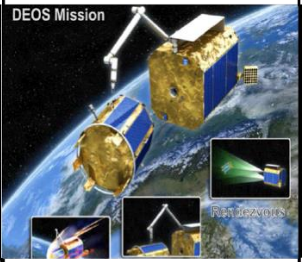
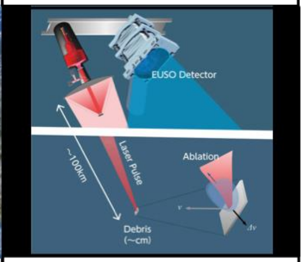
Exhibit 4 Satellite Network Concentration



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

Exhibit 5 Examples of Deorbiting Technologies

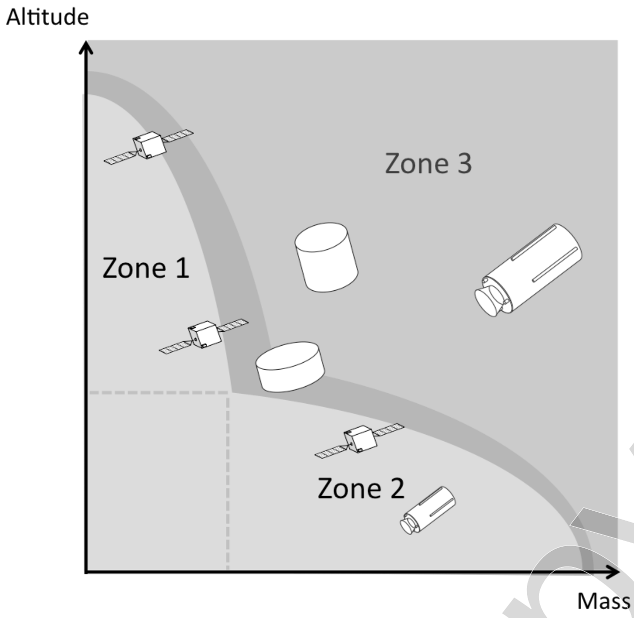


Space Agencies (Examples)			Non-space agencies
Japan/JAXA	Europe/ESA	Europe/DLR	Riken
PULL	PULL	PUSH	CONTACTLESS
			
An electrodynamic tether (EDT) is designed to generate electricity that will slow down space-based debris. The slowed-down space debris will fall into lower and lower orbits until burning 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.

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 6 Debris Removal Targets



Zone 1
De-orbit with Electric Propulsion System (ION)

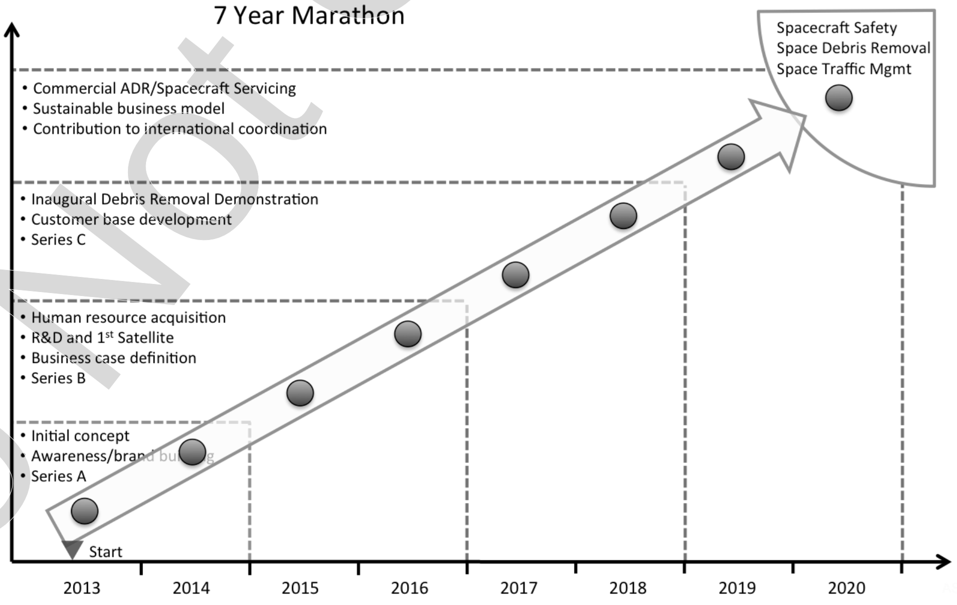
Zone 2
De-orbit with Solid Rocket Booster (SRB)

Zone 3
De-congestion and re-orbit with SRB

Source: Company.

Note: Astroscale was initially targeting Zone 1 (light debris in higher LEO orbits) and Zone 2 (heavier objects in lower LEO orbits) types of debris.

Exhibit 7 Astroscale's 7 Year Marathon strategy



Source: Company.

Exhibit 8 Astroscale *Lunar Dream* Time Capsule Design

Source: Company.

Endnotes

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