Remediating Space Debris

Legal and Technical Barriers

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Space. The word says it all: a pristine expanse with boundless potential and enough room for anything we could throw at it. However, words can be misleading. Outer space may be nearly boundless, but the neighborhood we populate is not. Currently about 500 operational satellites are in low Earth orbit (LEO), about 80 in medium Earth orbit (MEO), and about 400 in geosynchronous orbit (GEO).[1] Accompanying those working instruments are 17,000 pieces of catalogued debris in LEO; 1,000 in MEO; and 1,000 in GEO.[2] Every one of those measurable space objects is hurtling around the globe at an astonishing 7–12 kilometers per second, topping speeds on the imperial scale of 15,000 miles per hour.[3] One need only conduct a Google image search for *satellite* to see that space—at least the part of it that we have to contend with—is far from spacious. Moreover, the threat of space debris in a crowded Earth orbit has significant national security implications.

Such debris not only constitutes a hazard to life on the planet but also, as a loaded minefield, can precipitate a considerable loss of critical infrastructure. Yet, little progress has occurred in the remediation of space debris. This article highlights some of the significant legal and technological barriers to implementing such remediation, with political considerations intermixed in both, concluding that alleviating legal restrictions is the better avenue for encouraging any meaningful focus on this issue.

Trackable (orbital) debris, is a catchall term for any nonoperational piece of hardware in orbit. Particulates can range from a detached screw to an entire dislodged booster. The smaller (1–10 centimeters) remnants of disintegrated and exploded satellites number in the millions, and, despite being the size of paint chips, they can easily kill an astronaut on a space walk or rip a hole through the *International Space Station*. Furthermore, though fewer in number, larger pieces of space junk—such as decommissioned satellites or abandoned segments of flight vehicles—pose a considerable risk across LEO and to the constellations of tightly orchestrated satellites in GEO. Larger debris presents a greater future risk of fragmentation; thus, their removal disproportionately benefits orbital stability.

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Antisatellite (ASAT) missile tests (such as the Chinese Fengyun trial), orbital collisions (such as the Cosmos-Iridium crash), and jettisoned capsules are among the principal sources of these materials. So why should the United States care?

First, reentering material threatens infrastructure and people, potentially leaving a wake of destruction on Earth's surface that, although sounding like science fiction, occurs far more frequently than commonly believed. For example, in 1978 a Russian spy satellite (*Cosmos 954*) failed to separate from its nuclear reactor before reentry, littering the Canadian arctic with radioactive debris when it crashed. In 1979 the American *Skylab* space station descended uncontrolled, striking parts of western Australia. More recently, four solid rocket motors have crash-landed in Uruguay, Saudi Arabia, Thailand, and Argentina since 2001.[4] Second, the *International Space Station* is also frequently at risk of damage, placing in danger the lives of astronauts on board and in transit. By some estimates, over the course of a typical mission, space shuttles confronted a 1-in-250 chance of suffering catastrophic damage from a high-velocity micrometeor or piece of debris.[5] In the course of 100 missions, that risk would reach a cumulative 33 percent—an admittedly dramatic but illustrative assessment.[6] Finally, space junk could disable a host of satellites critical to global commerce, national defense, international navigation, and agriculture.

So why not simply launch the space vacuums and clean up the mess we have made? As with many international crises, the solution to this issue is far more complicated than the circumstances that created it. A host of legal, political, and technical considerations persist in making space debris a topic of frustration. Everyone agrees that something must be done; very few agree on just exactly what that something is. Preventing the creation of future debris has been a rallying point for a number of spacefaring nations. However, it is a Band-Aid fix to a still-growing problem, albeit one that encourages greater utilization of technology and personal responsibility among agencies the world over. Still, as long as trash continues to clutter the skies, the risk to national security and economy will persist. Some observers, such as Donald Kessler, a physicist with the National Aeronautics and Space Administration (NASA), even suggest an instance of critical mass at which time the abundance of debris material in LEO could cascade into perpetual chain-reaction accidents—a phenomenon known as the Kessler syndrome.[7] Reports circulated by NASA's Johnson Space Center support at least some aspect of Kessler's theory: even had all launches stopped in 2005, the preexisting cloud of orbital trash at the time was large enough to continue creating debris faster than atmospheric drag could remove it.[8] Thus, although attempts at debris mitigation are critical to having some effect on long-term sources of debris from ASAT explosions and ejected mission modules, such limited efforts do not offer a solution to the wider problem. The overall clutter of catalogued debris likely would continue to increase even if satellite launches stopped tomorrow. Clearly, something must be done—but what?

Legal Barriers

Popular perception views technology as an exponentially expanding industry that, much like Moore's Law, continuously pushes its own boundaries. Such rapid growth is infrequently, if ever, matched by an equal evolution in the legal framework that governs it. Consequently, in many ways the controlling space law and treaties are hindrances to addressing contemporary problems because of their obtrusively outdated nature. In 1967 the United States signed the Outer Space Treaty (OST), which broadly defined the most significant Cold War aims of what was then a bipolar celestial contest. In 1968 the United States and USSR added an Astronaut Rescue Treaty to this agreement, and in 1972 the Liability Convention became another addendum. By 1979 both the Registration Convention and the Moon Agreement had become final caveats to this body of international law.[9] Since then, governments have necessarily oriented space law around this paradigm, producing results which have not always been favorable to meeting burgeoning contemporary challenges.

First and most significantly, as of 2006, no international agreement or United Nations (UN) document had used or defined the term *space debris*.[10] It is impossible to address a problem that is neither identified nor institutionally acknowledged. Admittedly, Article IX of the OST condemns the harmful contamination of space although it does so in a rhetorical fashion and without mechanisms for enforcement or clear understanding of what contamination means.[11] Aiding in the reluctance of states to engage in a discussion on this topic is the inclusion of Articles VI and VII in the OST. Together, they form a broad conceptualization of liability in which a state is liable not only for the material it launches but also for any orbital devices launched by nongovernmental entities within that state's domestic borders.[12] In 1967 when the United States and Soviet Union were the only two nations with serious space capabilities and their respective governments provided the launch sites and overall vision for the space industry, that clause was a minor matter. Today, when space technology has become an ever-growing component of global commercial activities and when the space community has become increasingly commercialized (and eventually privatized), Articles VI and VII heap an overwhelming degree of liability on states, given the prevalence of corporations currently in the space business.

Ironically, the similarly outdated 1972 Liability Convention further complicated the question of fault. This convention attempted to define negligence in a manner that would encourage the international community to behave responsibly in space. However, for such an agreement to have any considerable effect on debris remediation, its tenets must be straightforward and enforceable. Such is not the case. The first and most critical determination to make in exposing liability is the identification of objects involved in a given collision. In 1972 tracking equipment that could have any meaningful technological effect on these talks did not exist. Furthermore, although US Strategic Command's (USSTRATCOM) contemporary Space Surveillance Network has a far greater capability to detect and monitor orbital debris, it is far from perfect and not universally accessible. Yet, even if a claimant could accurately identify the party involved in an orbital collision, the issue of negligence remains to be determined. Legally, deciding the orbital parameters is the last affirmative action taken by a state in launching a satellite (without standard station-keeping maneuvers); merely launching a satellite does not constitute negligence.[13] Some individuals believe that Inter-Agency Space Debris Coordination Committee guidelines, expanded International Telecommunication Union registration, or the standard practice of boosting payloads to graveyard orbits offers avenues for assigning fault to those who do not comply with such norms in the future. To date, however, no dominant, rules-based order has reached global consensus.

Finally, the Liability Convention leaves us without a clear answer to the question of what constitutes causation. We have no rules of the road in space—no way of telling who was driving in the wrong lane or who ran a red light (only GEO slots require registration with the International Telecommunication Union). Moreover, functional satellites can often maneuver small distances. If a nonoperational piece of debris struck an operational satellite that did not jettison (move out of the way), is that contributory negligence? So far, because such questions have no firm answers, catastrophic events like Fengyun continue to pollute near Earth orbits, and the international community feels no legal compulsion to act. In reality the Liability Convention did not convene with the intention of protecting space; rather, it was a political treaty meant to solidify key national interests in still poorly understood technical and judicial fields.[14] Still, without a compelling legal (and consequently economic) incentive to patrol space, the remediation of refuse will continue to be purely a matter of lip service for most states.

For argument's sake, let us assume that states genuinely wanted to fix this problem and agreed to uniformly address every issue raised thus far. Only a handful of nations can actually remove debris from LEO, MEO, and GEO (mainly the United States and Russia). Imagine, in a joint project, that these states develop a clever mechanism for the remediation of medium to large pieces of nonoperational orbital material. Despite these efforts, according to both the OST and the Registration Convention, salvage rights in orbit do not exist. Anything put into space remains the property of the entity that launched it—even if that property explodes into 5,000 pieces. Therefore it is illegal to move or remove any object in space that does not belong to the launching state or state of registry performing the action—at least not without permission.[15] The provisions of the OST's Article VIII, which embodies this rule, may therefore bar Russian or US efforts to clean up debris in this scenario, assuming, of course, that states can even identify the owner of a certain piece of debris—no simple task. Further, lest we forget, what if in the effort to clean up debris, we create more? In that circumstance, we would find ourselves back at the circular discussion of liability.[16]

As we can see, remediation of space debris meets its first major obstacle in the perplexing legal regime that makes incentivizing action through liability and ownership laws ambiguous and difficult to enforce. To be sure, some solutions are being considered as pressure mounts to solve this worrisome problem. Damage-compensation funds, apportionment of damages based on market-share liability, and fault-based standards for damages have all been suggested.[17] None has achieved consensus, but the mere fact that such matters are under discussion is a promising indication that the issue of remediating space debris is gaining ground. However, until liability, ownership, causation, rules of the road, and negligence are clarified and orbital debris is officially codified as a problem, motivation for greater action will continue to languish.

This reluctance among states to interact within a maladaptive legal system surrounding the space environment, expressed in the lethargy of international action, also finds roots in domestic political and defense considerations. Any conversation about the legislative regime cannot be disentangled from the rationale driving state actors. For many nations, reluctance to address this subject is driven largely by the defense apparatus. In the United States, NASA and the Department of Defense (DOD) have historically partnered on the topic of debris mitigation and adhere to strict guidelines as a means of helping reduce space debris.[18] Similarly, such efforts have passed the UN General Assembly for simple enough reasons: everyone can agree that creating even more space junk is a bad idea. Additionally, although the 2010 US *National Space Policy* instructed NASA and the military to pursue research and development on debris remediation, the policy lacked any timetable, rendering the instruction functionally useless.[19] Additionally, the government has yet to seriously task any agency with actually removing any debris, adding to the confusion in Washington.[20]

One reason for this disinterest in remediation stems from the types of technology that space cleanup would produce. Similar to concerns over satellite-maintenance craft, the ability to dock and tamper with another satellite or fragment thereof leads inevitably to issues of dual use (civil and military applications of a related hardware) in space technology. For example, a craft that could patrol and collect small debris could similarly be tasked to deorbit components of satellites belonging to another nation or competitive entity. The DOD and its counterparts in major spacefaring nations such as Russia and China have no interest in promoting the growth of such capabilities—not because they favor orbital clutter but because a civil technology that would remedy the problem invariably carries with it national security ramifications. As space trash nears critical mass, such priorities may shift. Until that time, those in favor of investment in space debris technology and legislation will continue to meet strong opposition among governments.

Technical Barriers

So what can be done about existing debris? The answer, on the hardware side, is some method of active debris removal (ADR)—an industry moniker for "something." Recent events, such as the Chinese ASAT test in 2007 and the collision of Russian (*Cosmos 2251*) and American (*Iridium 33*) satellites in 2009, have brought increased attention (and refuse) to the topic of debris remediation.[21] One cannot overstate how critical an issue debris has become as a consequence of these two instances. Together, they have increased trackable material by nearly one-third. In response, the technical community has been tasked, despite the immense barriers noted in the previous section, with exploring some realistic and economical ADR systems for deployment within a reason-able though unspecified time frame. However, something seemingly as simple as requesting designs for ADR concepts is inevitably tied up in myriad technical and political considerations. This section outlines some of the obstacles to technological innovation in this field, with a heightened focus on the impact of policy choices on the developing technology.

Technical developments in fields that project little to no short- or medium-range economic advantages do not tend to garner private resources. Some people believe that government research grants should fill this gap—a belief implying that, for better or for worse, political considerations directly affect the migration of technology in such industries. The effects of this correlation are obvious in highly politicized debates on climate change or stem cell research. Moreover, despite the lower profile, this relationship plays an equally significant a role in ADR investment. Because defense concerns and legal uncertainties motivate governments to defend the status quo, no profound government push has driven technological developments. Furthermore, even should political motivations converge to produce a discernible mandate for ADR research, engineers will inevitably face constricting parameters from defense agencies concerned about dual-use applications. For example, a giant laser (an actual suggestion) designed to heat up one side of a piece of debris, causing it to collapse out of orbit, is essentially a giant ray gun. If it can deorbit a decommissioned satellite, then it can just as easily disable an operational one.

Additionally, assuming the existence of positive responses from the defense community, a favorable legal climate, and supportive American political will, there remains a point of debate regarding exactly what type of ADR projects merit the limited resources made available to the Defense Advanced Research Projects Agency and NASA. Such determinations would require prioritizing either the removal of smaller debris, which aids in safeguarding existing operational satellites, or the remediation of larger debris, which contributes to the long-term stability of orbital systems.[22] Arguments for the former stress the use of tight resources in addressing immediate issues. Small debris is problematic to track, and the number of individual pieces extends into the millions. Difficulty cataloguing and monitoring so much debris means that objects like paint chips and loose screws present the greatest short-term threat to operational satellites. Arguments for the latter stress the projections that removing even as few as five of the highest-risk large pieces of debris can considerably stabilize the orbital environment.[23] Because actors can easily catalogue large debris, such materials present a more limited immediate threat. However, as noted above, the fragmentation potential of a big piece of orbiting junk presents an outsized, long-term risk. This vulnerability will inevitably need to be addressed although the necessarily myopic nature of politics (and the presence of more pressing considerations) makes the seemingly simple task of removing only a handful of pieces of debris difficult.

Similarly, policy makers face a related choice between targeted and dragnet technologies, each posing its own benefits and issues as well.[24] Dragnets are particularly useful after a catastrophe, cleaning up clusters of debris before they spread by capturing a large amount of material—similar to a trawler dredging the ocean floor. However, dragnets may be just as undiscerning as a dredge—inexact in what they collect. Targeted techniques may be more equipped to mitigate the chances of specific collisions. Thus, assuming that we can address all of the political, legal, security, economic, and prioritization problems, what technology is currently available for research investment?

The first step in answering that question involves enhancing situational awareness in space. To date, only USSTRATCOM monitors space debris in anything resembling a comprehensive fashion, opening a host of ethical questions on its own. For instance, is the United States obligated to warn a foreign company or country of an impending collision? However, this single monitoring task relies on aging technology to track only tens of thousands of the millions of pieces of man-made junk in space. In 2013 sequester constraints forced the US government to scrap an S-band radar system known as Space Fence, representing an attempt to upgrade some of the infrastructure the joint force uses to track space debris. In June 2014, the government revitalized the program, awarding Lockheed Martin a contract of nearly one billion dollars to resume work on the project. The legacy tracking system can track debris around the size of a basketball in LEO whereas the proposed Space Fence will be able to track debris down to the size of a baseball or smaller.[25] This increased ability could result in the number of catalogued pieces of debris shifting from nearly 20,000 to closer to 200,000.[26] Yet, no matter whether Space Fence survives future cuts, any attempt at debris remediation will require affording USSTRATCOM the resources to continue combing software-based predictive models enhanced by a growing ability to spot-check more debris. Such a capability is a prerequisite to any attempt at remediation since we cannot remove what we cannot find. Similarly, enhanced situational awareness contributes to alleviating a number of the technical issues plaguing the debate on liability.

Yet, eventually, remediation will demand the physical removal or deorbiting of space debris, and we have no shortage of proposals on how to do that. One popular concept in circulation calls for use of a tether, utilizing either electromagnetics or momentum exchange. Such devices usually target larger debris, causing such materials to drop out of LEO or flinging them into graveyard orbits above GEO—in much the same way an object tied to a rope can be sent flying. The electrodynamic variant has gained prominence recently: a $1.9 million grant from NASA to Star Technology and Research made news in March 2012.[27] The advertised layout of the company's ElectroDynamic Debris Eliminator used a fleet of 12 craft launched into LEO, working in unison to grab debris and drag it to short-lived orbits before cascading out of circulation. The company, which has received other government grants in the past, projected that a fleet of this size conceivably could remove all current LEO trash over two kilograms within seven years.[28] Consequently, although this targeted system carries with it the benefits of accuracy and control, it is designed to choreograph in such a manner that it produces the long-term benefits of a dragnet approach as well. Whether it can truly keep up with the natural increase of debris, whether deorbited material runs the risk of reaching the surface, and whether such a large and mobile fleet further increases the chances of collisions are questions that still need answers, leaving this regimen as one among a host of uncrowned contenders for the title of panacea. It joins the ranks of lasers and harpoons in the ever-growing club of designs vying for a slice of the inevitable windfall that a likely crisis would produce. Though just one example, the ElectroDynamic Debris Eliminator demonstrates the complexities involved at every level of technical development and the associated costs for even nonoperational prototypes.

Space is an incredibly hostile environment. The absence of atmosphere, high radiation levels, extreme temperatures, and the remote aspect of operations all make remediation a technical issue of the highest complexity. Additionally, with costs so exorbitant, outcomes so uncertain, priorities so ambiguous, and technologies still untested, ADR will continue to linger at the mercy of political whim. Only after such uncertainties are settled can the arduous process of technical trial and error begin. Space cleanup will not be a quick fix, and scientists concerned about the immediacy of the crisis undoubtedly will continue to see solutions pushed to the horizon until those who control the flow of funding are persuaded to make the necessary political and economic investments.

Finally, any discussion of the role of commercial air and space cannot ignore the reality that private industry is a growing segment of the launch-and-payload market. NASA increasingly relies on commercial partners (Orbital Sciences Corporation and Space Exploration Technologies Corporation [the latter more commonly referred to as SpaceX]) to meet its resupply obligations for the *International Space Station*. The Boeing Company, Sierra Nevada Corporation's Space Systems, and SpaceX also compete to provide commercial American access to LEO, a capability the United States has lacked since termination of the shuttle program in 2011. SpaceX announced in August 2014 that it had selected Brownsville, Texas, as the site of a private commercial spaceport where the company intends to conduct upwards of a dozen commercial launches annually. Given these developments as a backdrop, it is obvious that private corporations cannot simply look at space remediation as an industry cash cow. Air and space companies must be included in a regime that fairly distributes the responsibilities of debris prevention and remediation in a way that meets their role in the modern system. Updating the Liability Convention could provide one framework for helping expand the international legal and financial responsibilities of commercial launch companies. International bodies such as the International Telecommunications Union (a UN affiliate) offer yet another avenue within which policy makers can discuss this decidedly multinational issue. However, no matter the method for addressing the rights and responsibilities of private companies, any broader discussion of the legal and technical barriers to space debris remediation must recognize that this issue is no longer solely a governmental one.

Conclusion

Evidently, space debris is a complicated and inherently international topic having direct ramifications for national security. However, with material and responsibility spread among multiple nations and liability a major cause of concern for every participant, solutions can originate only in a global forum. Policy makers can address technical issues with funding; funding for such projects comes from the political establishment; and the political establishment listens to lawyers and generals. The best way to appease that core constituency is to reach a multilateral consensus on an international set of standards and programs that eliminate uncertainty and the fear of legal reprisal against those who seek to fix the problem. This is the capstone of barriers to space debris remediation. If nations could concur on fundamental negligence principles and rules of liability in this context, while uniting technologically (as they have done with the *International Space Station*) to respond to the issue, then the remaining conflicts would not disappear—but they would become far more manageable.

In a joint venture, the DOD could monitor openly the capabilities of participating agencies. Furthermore, it is inevitable that most military communities will eventually see debris as an unavoidable threat to national security. Thus, the status quo will not survive. With the defense community on board, political support for ADR becomes sustainable, consequently opening funding in the budget process, which large companies and entrepreneurs alike can manipulate to the gain of ADR research grants. Additionally, given an agreement on enforceable liability and causation standards, investment similarly will follow in enhanced monitoring and situational awareness capabilities. By establishing a coherent set of incentivizing ground rules, we expose the tangles of space debris remediation to realistic solutions. If the international community can come together, the cleanup of space refuse becomes a far more promising venture.

Notes

1. Secure World Foundation, *Space Sustainability: A Practical Guide* (Broomfield, CO: Secure World Foundation, 2014), 8, http://swfound.org/media/121399/swf_space_sustainability-a_practical_guide_2014__1_.pdf.

2. Ibid.

3. Noncatalogued pieces of debris are projected to be in the millions. Catalogued debris is only the material that current sensors can measure and spot-check.

4. National Aeronautics and Space Administration (NASA), "Reentry of U.S. Rocket Stage above South America," *Orbital Debris Quarterly News* 15, no. 3 (2011): 3. In none of these cases were lives lost, but they do represent the periodic (if infrequent) occurrence of dangerous reentries.

5. John Matson, "U.S. Taking Initial Steps to Grapple with Space Debris Problem," *Scientific American*, 31 August 2011, http://www.scientificamerican.com/article.cfm?id=orbital-debris-space-fence.

6. Ibid.

7. Kessler's calculations have been misapplied in pop culture, but the theory remains both viable and accepted as a theoretical scenario. In 2010 Kessler explained his updated position on the syndrome and his general support for the model it produced in the following paper: Donald J. Kessler et al., "The Kessler Syndrome: Implications to Future Space Operations" (paper presented at the 33rd Annual American Astronomical Society Guidance and Control Conference, Breckenridge, CO, 6–10 February 2010), http://webpages.charter.net/dkessler/files/Kessler%20Syndrome-AAS%20Paper.pdf.

8. NASA Orbital Debris Program Office, "Orbital Debris Remediation," Johnson Space Center, 21 August 2009, http://www.orbitaldebris.jsc.nasa.gov/remediation/remediation.html. A study referenced by

NASA concludes that the collision of satellites already in orbit by 2005 would eventually be enough to replace and exceed the amount of debris greater than 10 centimeters that would be lost to atmospheric drag. In other words, for every piece of debris that burned up in Earth's atmosphere, new accidents would create at least one new piece of debris even if we never launched another payload into space again.

9. Cesar Jaramillo, ed., *Space Security 2010: Executive Summary* (Kitchener, Ontario: Pandora Press, June 2010), 12, http://swfound.org/media/29036/ssi2010executivesummary.pdf.

10. Michael W. Taylor, "Orbital Debris: Technical and Legal Issues and Solutions" (LLM thesis, McGill University, 2006), 39–40, http://fas.org/spp/eprint/taylor.pdf.

11. Ibid., 76.

12. Ibid., 42.

13. Ibid., 77.

14. The Convention on International Liability for Damage Caused by Space Objects (Liability Convention) entered into force in 1972—five years after the signing of the Outer Space Treaty. The convention's most fundamental provision is that all liability for a launch is held by the launching state. Consequently, only states can make claims against one another under the convention guidelines; corporations and individuals are precluded from doing so. In 1972 these concepts were relatively uncontentious since only the superpowers could even think of launching satellites into orbit. However, in an increasingly commercialized and vastly expanded industry, private companies play an undeniable role in the launching of payloads and the ownership and operation of satellites in orbit. As a consequence, the international system is unlikely to embrace a legal regime that holds states entirely financially responsible for the impact of the actions of corporations or of individuals launching from within their borders. Equally, a regime that marginalizes an increasingly important community in the air and space industry—commercial launch operators—is sure to be nonfunctional. In fact, despite 89 signatures, the convention has been successfully used only once, in the case of the *Cosmos 954* crash mentioned earlier.

15. Taylor, "Orbital Debris," 80.

16. It is important to note that, no matter how significantly we address the inadequacies of the legal regime, collective action will always remain an obstacle to debris remediation. As with tackling climate change, cleaning space debris is an expensive project with few immediate prospects of financial gain for those actors who pay to address it. This author believes that an updated legal framework makes issues of collective action easier to discuss. Nevertheless, the fact remains that projects of collective origin and collective rectification are profoundly difficult political issues that, by definition, do not easily lend themselves to simple solutions.

17. Taylor, "Orbital Debris," 85.

18. Dave Baiocchi and William Welser IV, *Confronting Space Debris: Strategies and Warnings from Comparable Examples Including Deepwater Horizon* (Santa Monica, CA: RAND Corporation, 2010), 83, http://www.rand.org/content/dam/rand/pubs/monographs/2010/RAND_MG1042.pdf.

19. Matson, "U.S. Taking Initial Steps."

20. NASA Orbital Debris Program Office, "Orbital Debris Remediation."

21. Ibid.

22. Ibid.

23. Ibid.

24. Baiocchi and Welser, *Confronting Space Debris*, 46.

25. The new Space Fence will replace nine VHF-band radars with ground-based radar positioned on the Kwajelein Atoll in the Marshall Islands. The new detectors will use a compressed S-band to catalogue and spot-check objects down to the size of a baseball in LEO.

26. Josh Tallis, "Lockheed Wins Contract to Track Space Trash," *Spaceflight Insider*, 4 June 2014, http://www.spaceflightinsider.com/space-flight-news/lockheed-wins-contract-track-space-trash/.

27. Douglas Messier, "Company Gets $1.9 Million from NASA to Develop Debris Removal Spacecraft," *Parabolic Arc* (blog), 12 March 2012, http://www.parabolicarc.com/2012/03/12/company-gets-1-9-million-from-nasa-to-develop-debris-removal-spacecraft/.

28. "ElectroDynamic Debris Eliminator (EDDE) Vehicle," Star Technology and Research, accessed 15 December 2014, http://www.star-tech-inc.com/id121.html.