Remediating Space Debris

Legal and Technical Barriers

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Abstract

As with many international crises, the solution to space debris is far more complicated than the circumstances that created it. A host of legal, political, and technical considerations persists in making space debris a topic of frustration. Preventing future debris has been a rallying point for a number of spacefaring nations, but it remains a growing problem 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. Thus, while attempts at debris mitigation are critical to positively impacting long-term sources of debris, such limited attempts do not offer a solution to the wider problem. Something must be done. But what?

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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 there are over 500 operational satellites in low earth orbit (LEO); there are about 80 operational satellites in medium earth orbit (MEO); and there are around 400 operational satellites in geosynchronous orbit (GEO).[1] Accompanying those working instruments are 17,000 pieces of catalogued debris in LEO, 1,000 pieces in MEO, and 1,000 pieces in GEO.[2] Every single one of those measureable space objects is hurtling around the globe at an astonishing 7–12 kilometers per second, topping speeds on the imperial

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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 repercussions of a crowded earth orbit have significant national security implications through the threat of space debris.

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

Trackable debris, or orbital debris, is used as 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 can easily kill an astronaut on a space walk or rip a hole through the International Space Station. In addition, while 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, and thus, their removal has a disproportionate positive impact on orbital stability. Antisatellite (ASAT) missile tests (such as the Chinese Fengyun ASAT test), orbital collisions (such as the Cosmos-Iridium crash), and jettisoned capsules are among the largest 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, while sounding like science fiction, occurs far more frequently than is commonly believed. For example, in 1978, a Russian spy satellite (Cosmos 954) failed to separate from its nuclear reactor before reentry. Consequently, the Canadian arctic was littered with radioactive debris from the satellite crash. In 1979, the American Skylab space station descended uncontrolled, striking parts of Western Australia. More recently, four solid rocket motors 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 onboard and in transit. By some estimates, over the course of a typical mission, space shuttles faced the risk of a 1-in-250 chance of being catastrophically damaged by 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 has the potential to disable a host of satellites critical to global commerce, national defense, international navigation, and agriculture.

So why not simply send up 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 something must be done; very few agree on just what exactly 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 a fix 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, like National Aeronautics and Space Administration (NASA) physicist Donald Kessler, even suggest an instance of critical mass at which time the abundance of debris material in LEO could cascade into perpetual chain-reaction accidents. This phenomenon has been termed the Kessler syndrome.[7] Reports being 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 was, at the time, large enough to continue creating debris faster than atmospheric drag could remove it.[8] Thus, while attempts at debris mitigation are critical to positively impacting long-term sources of debris from ASAT explosions and ejected mission modules, such limited attempts do not offer a solution to the wider problem. The overall clutter of catalogued debris would likely continue to increase even if satellite launches stopped tomorrow; something must be done. But what?

Legal Barriers

In popular perception, technology is seen 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, the controlling space law and treaties are, in many ways, hindrances to addressing contemporary problems because of their obtrusively outdated nature. In 1967, the United States signed the Outer Space Treaty (OST), broadly defining the most significant Cold War aims of what was then a bipolar celestial contest. In 1968, the United States and USSR included an Astronaut Rescue Treaty to this agreement and, in 1972, the Liability Convention was added as another addendum. In 1979, both the Registration Convention and the Moon Agreement were final caveats to this body of international law.[9] Since then, governments have necessarily oriented space law around this paradigm, and the result has not always been favorable to meeting mounting contemporary challenges.

First and most significantly, as of 2006, no international agreement or UN document uses or defines the term "space debris."[10] It is impossible to address a problem that is neither identified nor institutionally acknowledged. Concededly, Article IX of the OST condemns the harmful contamination of space, though 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, these sections form a broad conceptualization of liability in which a state is not only liable for the material it launches, but is also liable for any orbital devices launched by nongovernmental entities within that state's domestic borders.[12] In 1967, when the United States and the 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, with space technology an ever-growing component of global commercial activities and with increased commercialization (and eventual privatization) of the space community, 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 was an attempt to define negligence in a manner to encourage the international community to behave responsibly in space. However, for such an agreement to have any considerable impact on debris remediation, its tenets must be straightforward and enforceable. The convention produced neither. The first and most critical question to answer in exposing liability is the identification of what objects were involved in a given collision. In 1972, tracking equipment did not exist to make any meaningful technological impact on these talks. And while today US Strategic Command's (USSTRATCOM) Space Surveillance Network has a far greater capability to detect and monitor orbital debris, this ability is far from perfect and is not universally accessible. Yet even if a claimant could accurately identify who was involved in an orbital collision, the issue of negligence still has to be determined. Legally, the last affirmative action a state takes in launching a satellite (sans standard station-keeping maneuvers) is deciding its orbital parameters; merely launching a satellite does not constitute negligence.[13] Some believe that Inter-Agency Space Debris Coordination Committee guidelines, expanded International Telecommunication Union (ITU) registration, or the standard practice of boosting payloads to graveyard orbits offer avenues for assigning fault against those who do not comply with such norms in the future. But to date, no dominant rules-based order has reached global consensus.

Finally, the Liability Convention leaves us without a clear answer as to what constitutes causation. There are no rules of the road in space—no way of telling who was driving in the wrong lane or who blew a red light (only GEO slots even require registration with the ITU). Furthermore, 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, there are no firm answers to questions like this, and consequently, catastrophic events such as Fengyun continue to pollute near earth orbits, while the international community feels no legal compulsion to act. In reality, the Liability Convention was not convened with the intention of protecting space; 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 states genuinely wanted to fix this problem and agreed to uniformly address every issue raised thus far. Only a handful of nations have the capability to 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-sized nonoperational orbital material. Despite these efforts, according to both the OST and the Registration Convention, there is no such thing as salvage rights in orbit. Anything put into space remains the property of the entity that launched it—even if that property explodes into 5,000 pieces. It is therefore illegal to move or remove any object in space that does not belong to the launching state or state of registry—at least to do so without permission.[15] Article VIII of the OST, which embodies this rule, may therefore bar Russian or US efforts to clean up debris in this scenario. This is, of course, assuming states can even identify who owns a certain piece of debris, which, as noted, is not a simple task. And 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 on liability.[16]

As we can see, remediation of space debris meets its first major obstacle in the perplexing legal regime that makes incentivizing through liability and ownership laws ambiguous and difficult to enforce. To be sure, there are solutions being considered as pressure mounts to solve this worrisome problem. Damage-compensation funds, apportioning damages based on market-share liability, and fault-based standards for damages have all been suggested.[17] While none has achieved a consensus, the mere fact that such matters are under discussion is a promising indication that the issue of space debris remediation 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, while expressed in the lethargy of international action, also finds roots in domestic political and defense considerations. Any conversation on the legislative regime cannot be disentangled from the rationale driving state actors. For many nations, reluctance on 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 in an effort to help reduce space debris.[18] Such efforts have likewise passed the United Nations General Assembly, for simple enough reasons: everyone can agree that creating even more space junk is a bad idea. In addition, while 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 performing any debris removal, adding to the confusion in Washington.[20]

One reason for this disinterest in remediation is a result of the types of technology 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 in space technology. Dual use is a reference to the civil and military applications of a related hardware. 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. This is not because these agents favor orbital clutter but because space debris is so far favorable to the investment in a civil technology that 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), which is 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 reasonable though unspecified timeframe. 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 believe government research grants should fill this gap. This belief implies that, for better or for worse, political considerations directly affect where technology in such industries migrates. The impacts of this correlation are obvious in highly politicized debates on climate change or stem cell research. Moreover, despite the lower profile, this relationship plays just as 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 discernable 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, it can just as easily disable an operational one. Furthermore, 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 difficult to track, and the number of individual pieces extends into the millions. Difficulty cataloguing and monitoring so much debris means that things 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 large piece of orbiting junk presents an outsized, long-term risk. This risk will inevitably need to be addressed, though 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, policymakers face a related choice between targeted and dragnet technologies, each posing their 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 as undiscerning as a dredge as well—inexact in what they collect. Targeted techniques may be more equipped to mitigate the chances of specific collisions. So, assuming all of the political, legal, security, economic, and prioritization problems can be addressed, 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 ethics questions on its own. For example, 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, the US government scrapped an S-band radar system known as Space Fence, due to sequester constraints. This system was an attempt to upgrade some of the infrastructure the joint force uses to track space debris. In June 2014, 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. 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 amount of catalogued 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 that USSTRATCOM be afforded 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 attempts at remediation, as we cannot remove what we cannot find. Likewise, enhanced situational awareness contributes to alleviating a number of the technical issues plaguing the debate on liability.

Yet, eventually, debris remediation will require the physical removal or deorbiting of space debris, and there is no shortage of proposals on how to accomplish this. One popular concept being circulated is the use of a tether, utilizing either electromagnetics or momentum exchange. Such devices usually focus on larger debris, causing such materials to drop out of LEO or flinging them into graveyard orbits above GEO—much in the way an object tied to a rope can be sent flying. The electrodynamic variant has gained prominence recently, with a $1.9 million grant from NASA to Star Technology and Research making news in March 2012.[27] The advertised layout of their ElectroDynamic Debris Eliminator (EDDE) used a fleet of twelve crafts 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 could conceivably remove all current LEO trash over two kilograms within seven years.[28] Consequently, while this is a targeted system carrying 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 still needing to be answered, leaving this regiment 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 to be made from a likely crisis. While just one example, the EDDE demonstrates the complexities involved at every level of technical development and the associated costs for even nonoperational prototypes.

Space is an incredibly hostile environment. No 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 high, outcomes so uncertain, priorities so ambiguous, and technologies still untested, active debris removal 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 will undoubtedly 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 aerospace 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 are also in competition to provide commercial American access to LEO, a capability the United States has lacked since the 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. With these developments as a backdrop, it is obvious that private corporations cannot simply look at space remediation as an industry cash cow. Aerospace 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 with which to help expand the international legal and financial responsibilities of commercial launch companies. International bodies such as the International Telecommunications Union (a United Nations 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 this is no longer solely a governmental issue.

Conclusion

Space debris is evidently a complicated and inherently international topic, with 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 only originate 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, the remaining conflicts do not disappear, but they do 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. This consequently opens funding in the budget process, which large companies and entrepreneurs alike can manipulate to the gain of ADR research grants. Additionally, with an agreement on enforceable liability and causation standards, investment will likewise 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. Until then, space junk will continue to fill our horizon and remain among the greatest potential threats to America's critical infrastructure. SSQ

Notes

1. Secure World Foundation, *Space Sustainability: A Practical Guide* (Washington, DC: Secure World Foundation, 2013), 8, http://swfound.org/media/121399/swf_space_sustainability-a_practical_guide_2014__1_.pdf.

2. Ibid.

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

4. 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 Kessler, Nicholas Johnson, J. C. Liou, and Mark Matney, "The Kessler Syndrome: Implications to Future Space Operations" (paper, 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 web site, 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-cm that would be lost to atmospheric drag. In other words, for every piece of debris that burned up in the 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. Secure World Foundation, *Space Security Index, Space Security 2010: Executive Summary* (Washington, DC: Secure World Foundation), 12, http://swfound.org/media/29036/ssi2010executivesummary.pdf.

10. Michael W. Taylor, "Orbital Debris: Technical and Legal Issues and Solutions" (L.L.M. thesis, McGill University, 2006), 39–40.

11. Ibid., 76.

12. Ibid., 42.

13. Ibid., 77.

14. The Convention on International Liability for Damage Caused by Space Objects (Liability Convention for short) 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 were relatively uncontentious concepts, as only the super powers 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, a legal regime that holds states entirely financially responsible for the impact of actions of corporations or individuals launching from within their borders is one unlikely to be embraced by the international system. Equally, a regime that marginalizes an increasingly important community in the aerospace industry—commercial launch operators—is sure to be nonfunctional. In fact, despite 89 signatures, the convention has only ever been successfully used 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 little immediate prospects of financial gain for those actors who pay to address it. It is my position 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, are not easily lent 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.

19. Matson, "U.S. Taking Initial Steps," http://www.scientificamerican.com/article.cfm?id=orbital-debris-space-fence.

20. NASA Orbital Debris Program Office, "Orbital Debris Remediation," http://www.orbitaldebris.jsc.nasa.gov/remediation/remediation.html.

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. Joshua 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. STAR, Inc., "ElectroDynamic Debris Eliminator (EDDE) Vehicle," n.d., http://www.star-tech-inc.com/id121.html.

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