1

Active Space Debris Removal: Needs, Implications, and Recommendations for Today's Geopolitical Environment

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Space debris increasingly threatens the provision of satellite services that have become integrated into the operations of the global economy and U.S. military, such as GPS precision timing and navigation. While studies suggest that annually removing as few as five massive pieces of debris in critical orbits could significantly stabilize the space debris environment, countries have hesitated to develop space debris removal systems due to high costs and classic free rider problems. This paper argues that the United States should take the lead in immediately developing systems to remove space debris with the greatest potential to contribute to future collisions. Although leading by example will entail certain costs and risks, U.S. leadership in preserving the near-Earth space environment will result in not only long-term benefits for the United States, but also the fulfillment of U.S. national space policy and broader U.S. foreign policy objectives.

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I. Introduction

There are currently hundreds of millions of space debris fragments orbiting the Earth at speeds of up to several kilometers per second. Although the majority of these fragments result from the space activities of only three countries—China, Russia, and the United States—the indiscriminate nature of orbital mechanics means that they pose a continuous threat to all assets in Earth's orbit. There are now roughly 300,000 pieces of space debris large enough to completely destroy operating satellites upon impact (Wright 2007, 36; Johnson 2009a, 1).

It is likely that space debris will become a significant problem within the next several decades. Predictive studies show that if humans do not take action to control the space debris population, an increasing number of unintentional collisions between orbiting objects will lead to the runaway growth of space debris in Earth's orbit (Liou and Johnson 2006). This uncontrolled growth of space debris threatens the ability of satellites to deliver the services humanity has come to rely on in its day-to-day activities. For example, Global Positioning System (GPS) precision timing and navigation signals are a significant component of the modern global economy; a GPS failure could disrupt emergency response services, cripple global banking systems, and interrupt electric power grids (Logsdon 2001).

Furthermore, satellite-enabled military capabilities such as GPS precision-guided munitions are critical enablers of current U.S. military strategies and tactics. They allow the United States to not only remain a globally dominant military power, but also wage war in accordance with its political and ethical values by enabling faster, less costly warfighting with minimal collateral damage (Sheldon 2005; Dolman 2006, 163-165). Given the U.S. military's increasing reliance on satellite-enabled capabilities in recent conflicts, in particular Operation Desert Storm and Operation Iraqi Freedom, some have argued that losing access to space would seriously impede the ability of the United States to be successful in future conflicts (Dolman 2006, 165).

In light of these threats, certain measures have been taken to address the issue of space debris. In particular, internationally adopted debris mitigation guidelines are reducing the introduction of new fragments into Earth's orbit. However, there is a growing consensus within the space debris community that mitigation is insufficient to constrain the orbiting debris population, and that ensuring a safe future for space activities will require the development and deployment of systems that actively remove debris from Earth's orbit. The first-ever International Conference on Orbital

Debris Removal, held in December 2009 and co-hosted by the National Aeronautics and Space Administration (NASA) and Defense Advanced Research Projects Agency (DARPA), illustrated this growing concern.

At the same time, implementing active debris removal systems poses not only difficult technical challenges, but also many political ones. The global nature of space activities implies that these systems should entail some form of international cooperation. However, international cooperation in space has rarely resulted in cost-effective or expedient solutions, especially in areas of uncertain technological feasibility. Further, it will be difficult to quickly deploy these systems before the space environment destabilizes. Problems will also arise in dividing the anticipated high costs, as a small number of countries are responsible for the large majority of the space debris population, yet all nations will benefit from its removal.

This paper begins with an overview of the growing space debris problem to illustrate the need to develop and deploy active removal systems over the next several decades. It goes on to discuss the political challenges in developing and implementing effective systems and concludes with recommendations for organizing and managing a space debris removal program in today's geopolitical environment.

II. Basics of Space Debris

Definition

Space debris is a specific type of space object that is human-made, no longer functional, and in Earth's orbit. Space debris ranges in mass from several grams to many tons, and in diameter from a few millimeters to tens of meters. Fragments exist from roughly 100 to more than 36,000 kilometers above the Earth's surface. In 2009, NASA alone conducted nine in-orbit maneuvers to avoid potential collisions between its satellites and pieces of space debris (NASA 2010, 2).

The most dangerous pieces of space debris are those ranging in diameter from one to ten centimeters, of which there are roughly 300,000 in orbit. These are large enough to cause serious damage, yet current sensor networks cannot track them and there is no practical method for shielding spacecraft against them. Consequently, this class of orbital debris poses an invisible threat to operating satellites (Wright 2007, 36). Debris larger than ten centimeters, of which there are roughly 19,000 in orbit, can also incapacitate satellites but they are large enough to be tracked and thus potentially avoided. Debris smaller than one centimeter, in contrast, cannot be tracked or avoided, but can be protected against by using relatively simple shielding (Wright 2007, 36).

Observation and Tracking

Space object tracking is the process of predicting future locations of space objects and subsequently prescribing avoidance maneuvers to sidestep potential collisions. Tracking differs from simple observation and requires more complicated calculations and a network of strategically placed sensors around the globe. The U.S. military operates the world's largest collection of ground-based sensors for tracking space objects. Known as the Space Surveillance Network (SSN), it consists of twenty-nine globally distributed telescopes managed by the Joint Space Operations Center (JSpOC). Entities from Russia, China, and Europe currently have or are developing observation and tracking capabilities similar to those of the United States, though they are generally less capable.

Sources of Space Debris

There are many sources of space debris, including satellites that are no longer functional; mission related objects, such as tools lost by astronauts during extravehicular activities; and fragmentation events, which can be either accidental or intentional (Jehn 2008, 7). Fragmentation debris is the largest source of space debris. Three countries in particular are responsible for roughly 95 percent of the fragmentation debris currently in Earth's orbit: China (42 percent), the United States (27.5 percent), and Russia (25.5 percent) (NASA 2008, 3). Although this distribution of responsibility suggests that these countries should contribute more to cleaning up the near-Earth space environment than others, the fact that many nations will benefit from remediation results in a classic free rider problem that complicates the situation. Similar to the political challenges associated with an effective multilateral response to climate change, this uneven distribution of historic responsibility threatens to prevent or stall much-needed action.

Mitigation and Removal

There are two ways to reduce space debris: mitigation and removal. Mitigation refers to reducing the creation of new debris, while removal refers to either natural removal by atmospheric drag or active removal by human-made systems. Historically, the United States has been a leader in space debris mitigation; U.S. national space policy has included space debris mitigation since 1988, and the National Aeronautics and Space Administration (NASA) developed the world's first set of space debris mitigation guidelines in 1995. The Inter-Agency Space Debris Coordination Committee (IADC) serves as the leading international space debris forum; its mitigation guidelines (IADC 2002) were adopted by the United Nations Committee on the Peaceful Uses of Outer Space (COPUOS) and the General Assembly in 2007 and 2008, respectively.

Efforts to reduce space debris have focused on mitigation rather than removal. Although mitigation is important, studies show it will be insufficient to stabilize the long-term space debris environment. In this century, increasing collisions between space objects will create debris faster than it is removed naturally by atmospheric drag (Liou and Johnson 2006). Yet, no active space debris removal systems currently exist and there have been no serious attempts to develop them in the past. The limited number of historical impact events fails to give the situation a sense of urgency outside the space debris community. Further, though mitigation techniques are relatively cheap and can be easily integrated into current space activities, active removal will require developing new and potentially expensive systems. The remainder of this paper addresses the current space debris debate and options to develop effective space debris removal systems.

III. Recent Space Debris Events and the Current Debris Environment

There has been a steady growth of space debris since the launch of Sputnik in 1957, with jumps following two of the largest debris creating events in history: the 2007 Chinese anti-satellite (ASAT) test and the 2009 Iridium-Cosmos collision.

The first of these events occurred on January 11, 2007, when China intentionally destroyed its Fengyun-1C satellite while testing its newly developed ground-based ASAT system. It was the largest debris-creating event in history, producing at least 150,000 pieces of debris larger than one centimeter (NASA 2008, 3). The resulting debris has spread into near-polar orbits ranging in altitude from 200 to 4,000 kilometers. Roughly 80 percent of this debris is expected to stay in orbit for at least the next one hundred years and threatens to impact operating satellites (CelesTrak 2009). The test illustrates how a single unilateral action in space can create long-term implications for all space-faring nations and users of satellite services.

The 2007 Chinese ASAT test prompted criticism from major space powers regarding the reckless creation of space debris and the consequent threat to operational satellites (Clark and Singer 2007). It triggered debates over a range of issues, from banning space weapons to questioning future cooperation with China in space. Although these debates have not produced international agreements on complex issues such as the prohibition of space weaponization, they have highlighted the need for greater communication and transparency in space activities as the number of space-faring nations and non-state actors in space continues to grow (Pace 2009). Uncertainties surrounding the event have also raised larger political and security questions: the fact that the Chinese Foreign Ministry denied the test for several days after it became public suggests that there was a lack of communication between the People's Liberation Army, which ordered the test, and other parts of the Chinese government. Thus, beyond revealing China's military capabilities and ambitions, the test also raised questions as to whether China's stove piped bureaucracies make it an unreliable global partner in general (Bates and Kleiber 2007).

The second major space-debris creating event was the accidental collision between an active Iridium satellite and a defunct Russian military satellite on February 10, 2009. The collision created two debris clouds holding more than 200,000 pieces of debris larger than one centimeter at similar altitudes to those of the 2007 Chinese ASAT test (Johnson 2009b). It was the first time two intact satellites accidentally crashed in orbit, challenging the "Big Sky Theory," which asserts that the vastness of space makes the chances of a collision between two orbiting satellites negligible (Newman et al. 2009).

Iridium uses a constellation of sixty-six satellites to provide voice and data services to 300,000 subscribers globally. As the company keeps several spare satellites in orbit, the collision caused only brief service interruptions directly after the event (Wolf 2009). Nevertheless, the event was highly significant as it demonstrated that the current population of space objects is already sufficient to lead to accidental collisions, which, in turn, can lead to the creation of more space debris and increased risks to operational space systems. This type of progressive space debris growth is worrisome. The U.S. military, for example, relies on commercial satellites like Iridium for over 80 percent of its wartime communications (Cavossa 2006, 5).

IV. The Present and Future Space Debris Environment

Currently, the highest spatial densities of space debris are in near-polar orbits with altitudes of 800 to 1,000 kilometers. These are known as "critical orbits" because they are most likely to reach the point where the production rate of new debris owing to collisions exceeds that of natural removal resulting from atmospheric drag. They exist because several large fragmentation events have occurred in these regions, such as the two described above, and because debris lifetimes can last up to decades at these altitudes (Jehn 2008, 8).

Although the probability of catastrophic collisions caused by space debris has increased over the years, it remains relatively low and there have been only four known collisions between objects larger than ten centimeters (Wright 2009, 6). Nevertheless, the real concern is the predicted runaway growth of space debris over the coming decades. Such uncontrolled growth would prohibit the ability of satellites to provide their services, many of which are now widely used by the global community. Indeed, in a testimony to Congress for a hearing on "Keeping the Space Environment Safe for Civil and Commercial Uses," the Director of the Space Policy Institute at George Washington University, Dr. Scott Pace, stated that,

> …space systems such as satellite communications, environmental monitoring, and global navigation satellite systems are crucial to the productivity of many types of national and international infrastructures such as air, sea, and highway transportation, oil and gas pipelines, financial networks, and global communications (Pace 2009).

As early as 1978, scientists postulated that the runaway growth of space debris owing to collisional cascading would eventually prohibit the use of Earth's orbit (Kessler and Cour-Palais 1978). Recent scientific studies have also predicted uncontrolled debris growth in low-Earth's orbit over the next century. One NASA study used predictive models to show that even if all launches had been halted in 2004, the population of space objects greater than ten centimeters would remain stable only until 2055 (Liou and Johnson 2006). Beyond that, increasing collisions would create debris faster than debris is removed naturally, resulting in annual increases in the overall space object population. The study concluded that, "only the removal of existing large objects from orbit can prevent future problems for research in and commercialization of space" (Liou and Johnson 2006, 340). The European Space Agency (ESA) has come to similar conclusions using its own predictive models (ESA 2009a).

Consequently, there is growing international consensus in the space debris community that active removal will be necessary to prevent "collisional cascading," or the increasing number of collisions resulting from debris created from previous collisions, in Earth's orbit. The 5th European Conference on Space Debris concluded that, "active space debris remediation measures will need to be implemented in order to provide this sustainability…there is no alternative to protect space" (ESA 2009b). Similarly, Nicholas Johnson from NASA's Orbital Debris Program Office stated in a testimony to Congress that, "in the future, such collisions are likely to be the principal source of new space debris. The most effective means of limiting satellite collisions is to remove non-functional spacecraft and launch vehicle orbital stages from orbit" (Johnson 2009a, 2).

V. Active Space Debris Removal: Concepts and Challenges

Effectiveness of Debris Removal

A recent NASA study that simulated active debris removal over the next 200 years showed that certain pieces of space debris are more dangerous than others, in that they are more likely to cause debris-creating collisions (Liou and Johnson 2007). These more dangerous objects have masses of 1,000 to 1,500 kilograms and 2,500 to 3,000 kilograms; orbital inclinations of 70 to 75, 80 to 85, and 95 to 100 degrees; and orbital altitudes of 800 to 850, 950 to 1,000, and 1,450 to 1,500 kilometers. The study found that annually removing as few as five of these objects will significantly stabilize the future space debris environment (Liou and Johnson 2007, 3).

These results suggest that the threat posed by space debris could be significantly reduced by annually removing several large pieces from critical orbits. This would make effective space debris removal much more straightforward and potentially manageable by one nation or a small group of nations. In other words, the countries responsible for the majority of the current space debris population—China, Russia, and the United States—not only should take responsibility, but also now *can* take responsibility. Efforts to develop removal systems should begin immediately.

The Ideal Removal System

The ideal debris removal system should fulfill certain technical, economic, political, and legal requirements. Technical requirements include quick development and deployment, maximum use of proven technologies, and minimum introduction of new mass into orbit. Economic requirements involve a reasonable cost-to-benefit ratio, such that the inputted effort produces a noticeable improvement in the space debris environment. Political requirements include transparent development, deployment, and operations, such that other space-faring nations trust that the system will not be used to intentionally remove their active satellites from orbit. Finally, legal requirements should ensure compliance with existing international laws and standards, in particular the five United Nations treaties on outer space. These requirements are discussed in more detail in the remaining sections of this paper.

There is currently no man-made space debris removal system in operation, nor have there been any serious attempts to develop one. However, common concepts include electrodynamic tethers, solar sails, drag augmentation devices, orbital transfer vehicles, and space-based lasers. All of these have their own benefits and drawbacks, making it difficult to find a single system that fulfills all of the above requirements. For example, twelve electrodynamic tethers weighing only one hundred kilograms each could be launched as secondary payloads to stabilize the space debris population in low-Earth's orbit within five years (Foust 2009). However, tethers only work on objects greater than ten centimeters and attaching them to debris using conventional robotics would "incur excessive costs for the benefit gained" (Liou and Johnson 2006, 340-341). In contrast, a constellation of space-based lasers using photoablation to guide debris out of critical orbits could reach further than low-Earth's orbit, but would only work on debris smaller than ten centimeters. Moreover, the required laser technology is currently unavailable and launching a satellite constellation costs up to billions of dollars, making the development and deployment of such a system extremely expensive.

Challenges in Instituting Effective Space Debris Removal

There are substantial technical, economic, political, and legal barriers to developing, deploying, and operating active debris removal systems. Many current concepts rely on unproven technology, which means they will require substantial time and money to develop and deploy. The quantity of time and money required will vary with each concept, and detailed estimations are not publicly available because of the nascent state of the field. However, as a rough point of reference, it costs around $10,000 per kilogram to launch anything into orbit, making the cost of merely launching many of the aforementioned systems on the order of millions of dollars. Moreover, flagship missions at NASA, depending on their size, take five to ten years to plan, develop, and launch.

There is also a lack of clear policy on both national and international levels. Space-faring countries and the United Nations have only adopted mitigation guidelines and have not cited the development of active debris removal systems as part of their space policies. Moreover, there has been a lack of discussion about what entity is responsible for financing and operating these systems. This is a complicated issue as some nations have created more debris than others, yet all space-faring nations and users of satellites services would benefit from space debris clean up.

Provisions in the five United Nations outer space treaties must also be considered. For instance, Article VIII of the 1967 Outer Space Treaty states that nations retain jurisdiction and control over their space objects and that "ownership of objects launched into outer space…and of their component parts…is not affected by their presence in outer space or on a celestial body or by their return to Earth." This provision becomes significant when combined with the 1972 Liability Convention, which states that nations are internationally liable for damages caused by their space objects both in space and on Earth. Accordingly, before any debris is removed from orbit, consent from the appropriate country will need to be obtained. Using commercial companies to operate debris removal systems would not get around this problem of liability, as Article VI of the 1967 Outer Space Treaty makes countries responsible for the outer space activities of both their governmental and non-governmental entities.

Another major concern is the similarities between space debris removal systems and space weapons. Indeed, any system that can remove a useless object from orbit can also remove a useful one. There is an extensive and ongoing debate over space weapons, and in particular how to define them (Moltz 2008, 42-43). As the decades-long debate has failed to even produce a clear definition of the term, it will be nearly impossible to actively remove space debris without the use of devices that could be classified in some way as potential space weapons. Thus, openness and transparency will be an important element in the development, deployment, and operation of any space debris removal system so that it is not seen as a covert ASAT weapon.

The biggest challenge, however, will be simply starting the process of active debris removal. Despite growing consensus within the space debris community that active removal will be needed over the next several decades, the fact that space activities continue today without significant interference causes the larger global community to not see space debris as an issue. Moreover, space suffers from the "tragedy of the commons," a phenomenon that refers to the overexploitation of a shared resource when there is no clear ownership over it. This, in addition to the abovementioned challenges facing debris removal systems, means that the natural tendency of those in power will likely be to do nothing until they absolutely must. This is reminiscent of responses to climate change, where the failure of governments to take responsibility for their past actions and act preemptively is compromising the larger global good. Policy makers must therefore take necessary actions, as recommended in next section of this paper, to prevent what is now happening on Earth from also occurring in space.

Emerging Concepts

Recognition of the significant challenges facing space debris removal has sparked new interest in finding innovative solutions. On September 17, 2009, the U.S. Defense Advanced Research Projects Agency (DARPA) released a Request for Information (RFI) seeking to "identify possible technical approaches for cost effective and innovative system concepts for the removal of orbital debris." The RFI asked respondents to provide particulars about their concepts, such as an estimation of cost per kilogram of debris removed; an approach to complying with international goals of debris mitigation; and an approximate response time.

In addition to the RFI, DARPA also co-hosted with NASA the first ever International Conference on Orbital Debris Removal in December 2009. The conference was "dedicated to discussing issues, challenges, and specific concepts involved with removing man-made debris from Earth's orbit" and addressed "international politic[al] and legal concerns, safety issues, and economic constraints" (NASA 2009). The combination of this conference with the DARPA RFI will likely motivate new and innovative approaches to space debris removal needed to overcome the many aforementioned challenges. It is also a positive sign that the United States is taking the idea of space debris removal seriously.

VI. U.S. Leadership by Example

Need to Initiate Unilateral Action

International cooperation in space has rarely resulted in cost-effective or expedient solutions, especially in politically-charged areas of uncertain technological feasibility. The International Space Station, because of both political and technical setbacks, has taken over two decades to deploy and cost many billions of dollars—far more time and money than was originally intended. Space debris mitigation has also encountered aversion in international forums. The topic was brought up in COPUOS as early as 1980, yet a policy failed to develop despite a steady flow of documents on the increasing danger of space debris (Perek 1991). In fact, COPUOS did not adopt debris mitigation guidelines until 2007 and, even then, they were legally non-binding.

Space debris removal systems could take decades to develop and deploy through international partnerships due to the many interdisciplinary challenges they face. Given the need to start actively removing space debris sooner rather than later to ensure the continued benefits of satellite services, international cooperation may not be the most appropriate mechanism for instigating the first space debris removal system. Instead, one country should take a leadership role by establishing a national space debris removal program. This would accelerate technology development and demonstration, which would, in turn, build-up trust and hasten international participation in space debris removal.

Possibilities of Leadership

As previously discussed, a recent NASA study found that annually removing as little as five massive pieces of debris in critical orbits could significantly stabilize the long-term space debris environment (Liou and Johnson 2007). This suggests that it is feasible for one nation to unilaterally develop and deploy an effective debris removal system. As the United States is responsible for creating much of the debris in Earth's orbit, it is a candidate for taking a leadership role in removing it, along with other heavy polluters of the space environment such as China and Russia.

There are several reasons why the United States should take this leadership role, rather than China or Russia. First and foremost, the United States would be hardest hit by the loss of satellites services. It owns about half of the roughly 800 operating satellites in orbit and its military is significantly more dependent upon them than any other entity (Moore 2008). For example, GPS precision-guided munitions are a key component of the "new American way of war" (Dolman 2006, 163-165), which allows the United States to remain a globally dominant military power while also waging war in accordance with its political and ethical values by enabling faster, less costly war fighting with minimal collateral damage (Sheldon 2005). The U.S. Department of Defense recognized the need to protect U.S. satellite systems over ten years ago when it stated in its 1999 Space Policy that, "the ability to access and utilize space is a vital national interest because many of the activities conducted in the medium are critical to U.S. national security and economic well-being" (U.S. Department of Defense 1999, 6). Clearly, the United States has a vested interest in keeping the near-Earth space environment free from threats like space debris and thus assuring U.S. access to space.

Moreover, current U.S. National Space Policy asserts that the United States will take a "leadership role" in space debris minimization. This could include the development, deployment, and demonstration of an effective space debris removal system to remove U.S. debris as well as that of other nations, upon their request. There could also be international political and economic advantages associated with being the first country to develop this revolutionary technology. However, there is always the danger of other nations simply benefiting from U.S. investment of its resources in this area. Thus, mechanisms should also be created to avoid a classic "free rider" situation. For example, techniques could be employed to ensure other countries either join in the effort later on or pay appropriate fees to the United States for removal services.

Recommendations for Leadership in Space Debris Removal

Going forward, the U.S. government should engage the commercial sector in space debris removal. Government contracts with several commercial firms would create a competitive environment, encouraging innovation and cost minimization. Having several companies working on the problem at the same time would also accelerate remediation as several critical orbits could be addressed at once. Furthermore, early investments in a domestic space debris removal industry would give the United States a head start in what may become a critical industry over the coming decades.

The aforementioned 2009 International Conference on Orbital Debris Removal, co-hosted by DARPA and NASA, suggests that these two agencies could lead U.S. government efforts in space debris removal. However, it is important to recognize that DARPA and NASA are driven by very different motives: one is a civilian space agency, while the other is a defense research agency. Failure to appreciate these differences when establishing mission requirements could lead to a situation like that of the National Polar Environmental Satellite System (NPOESS), where the attempt to combine civil and military requirements into a single satellite resulted in doubling project costs, a launch delay of five years, and ultimately splitting the project into two separate programs (Clark 2010). Furthermore, any system developed through a joint NASA-DARPA partnership would need to be transferred to an operational agency, as both NASA and DARPA are research and development entities. The U.S. Air Force, as it is the primary agency responsible for national security space operations, is a possible option.

Funding the development of a national space debris removal system carries risks because, due to the nascent state of the field, detailed cost-benefit estimates have not yet been carried out. The Space Frontier Foundation, however, proposes that the government should establish special funds at the expense of parties who generate debris (Dunstan and Werb 2009). Suggested mechanisms for raising the funds include charging fees for U.S. launches based on the debris potential of the mission, with the size of the fee determined by relevant factors such as the mass of the anticipated debris resulting from the mission and the congestion of the orbit into which the space object is being launched. Satellite manufacturers, operators, and service providers could all share responsibility for payment into such funds. Once debris removal systems are in operation, additional funds could also come from service fees. For example, entities that created debris could pay a specified amount to removal providers in return for the service rendered.

Any national space debris removal program must also be kept transparent with ongoing international dialogue in forums such as COPUOS so that other nations can build-up trust in the effectiveness and efficiency of the program. A proven debris removal program will result in more productive discussions in these international forums.

VII. Conclusion

If the United States and other powerful governments do not take steps now to avert the potentially devastating effects of space debris, the issue risks becoming stalemated in a manner similar to climate change. Given the past hesitation of international forums in addressing the space debris issue, unilateral action is the most appropriate means of instigating space debris removal within the needed timeframe. The United States is well poised for a leadership role in space debris removal.

Going forward, the U.S. government should work closely with the commercial sector in this endeavor, focusing on removing pieces of U.S. debris with the greatest potential to contribute to future collisions. It should also keep its space debris removal system as open and transparent as possible to allow for future international cooperation in this field.

Although leadership in space debris removal will entail certain risks, investing early in preserving the near-Earth space environment is necessary to protect the satellite technology that is so vital to the U.S. military and day-to-day operations of the global economy. By instituting global space debris removal measures, a critical opportunity exists to mitigate and minimize the potential damage of space debris and ensure the sustainable development of the near-Earth space environment.

References

Bates, Gill and Martin Kleiber. 2007. China's Space Odyssey: What the Antisatellite Test Reveals About Decision-Making in Beijing. *Foreign Affairs*, May/June. http://www.foreignaffairs.com/articles/62602/bates-gill-and-martin-kleiber/chinas-space-odyssey-what-the-antisatellite-test-reveals-about-d (accessed February 20, 2010).

Cavossa, David. 2006. Statement before the House Subcommittee on Strategic Forces, June 21. http://www.globalsecurity.org/space/library/congress/2006_h/060621-cavossa.pdf (accessed February 22, 2010).

CelesTrak. 2009. *Chinese ASAT Test*. Center for Space Standards and Innovation. http://celestrak.com/events/asat.asp (accessed November 17, 2009).

Clark, Colin and Jeremy Singer. 2007. China's ASAT Test Widely Criticized: U.S. Says No New Treaties Needed. *Space News*, January 26.

Clark, Stephen. 2010. Budget Slashes NPOESS Weather Satellite Program. *Spaceflight Now*, February 1. http://spaceflightnow.com/news/n1002/01npoess/ (accessed February 2, 2010).

Dolman, Everett C. 2006. A Debate About Weapons in Space: For U.S. Military Transformation and Weapons in Space. *SAIS Review* 26(1): 163-175.

Dunstan, James E. and Bob Werb. 2009. *Legal and Economic Implications of Orbital Debris Removal: Comments of the Space Frontier Foundation*. In Response to: DARPA Orbital Debris Removal Request for Information for Tactical Technology Office, Solicitation Number: DARPA-SN-09-68.

European Space Agency (ESA). 2009a. *ESA Space Debris: Analysis and Prediction*. http://www.esa.int/esaMI/Space_Debris/SEMXP0WPXPF_0.html (accessed November 17, 2009).

—. 2009b. *Key Findings from the 5th European Conference on Space Debris*. http://www.esa.int/esaMI/Space_Debris/SEMYN9LTYRF_0.html (accessed November 19, 2009).

Foust, Jeff. 2009. Putting a bounty on orbital debris. *The Space Review*, July 27. http://www.thespacereview.com/article/1427/1 (accessed November 10, 2009).

Inter-Agency Space Debris Coordination Committee (IADC). 2002. *IADC Space Debris Mitigation Guidelines*. http://www.iadc-online.org/docs_pub/IADC-101502.Mit.Guidelines.pdf (accessed November 15, 2009).

Jehn, Rüdiger. 2008. "Introduction to the Problem of Space Debris." Lecture at the International Space University, Strasbourg, France, November 10.

Johnson, Nicholas L. 2009a. Statement before the House Subcommittee on Space and Aeronautics, Committee on Science and Technology, April 28. http://gop.science.house.gov/Media/hearings/space09/april28/johnson.pdf (accessed 27 November 2009).

—. 2009b. "Preserving the Near-Earth Space Environment with Green Engineering and Operations." Presentation at the Green Engineering Masters Forum, San Francisco, CA, September 30-October 2.

Kessler, Donald J. and Cour-Palais, B.G. 1978. Collisional Frequency of Artificial Satellites: The Creation of a Debris Belt. *Journal of Geophysical Research* 83 (June): 2637-2646.

Liou, J.-C. and Nicholas L. Johnson. 2007. "A Sensitivity Study of the Effectiveness of Active Debris Removal in LEO." Paper presented at the International Astronautical Congress, Hyderabad, India, September 21-28.

—. 2006. Risks in Space from Orbiting Debris. *Science* 311: 340-341.

Logsdon, John M. 2001. Just Say Wait to Space Power. *Issues in Science and Technology* Spring. http://www.issues.org/17.3/p_logsdon.htm (accessed September 18, 2009).

Moltz, James Clay. 2008. *The Politics of Space Security: Strategic Restraint and the Pursuit of National Interests*. Stanford: Stanford University Press.

Moore, M. 2008. Space War, the Logical Next Mistake for US Exceptionalism. *Disarmament Diplomacy* 87 (Spring).

National Aeronautics and Space Administration (NASA). 2010. *Orbital Debris Quarterly News* 14(1). http://orbitaldebris.jsc.nasa.gov/newsletter/pdfs/ODQNv14i1.pdf (accessed June 1, 2010).

—. 2009. *Orbital Debris Quarterly News* 13(4). http://orbitaldebris.jsc.nasa.gov/newsletter/pdfs/ODQNv13i4.pdf (accessed November 17, 2009).

—. 2008. *Orbital Debris Quarterly News* 12(1). http://orbitaldebris.jsc.nasa.gov/newsletter/pdfs/ODQNv12i1.pdf (accessed November 17, 2009).

Newman, Lauri Kraft, Ryan Frigm, and David McKinley. 2009. "It's Not a Big Sky After All: Justification for a Close Approach Prediction and Risk Assessment Process." Paper presented at the AAS/AIAA Astrodynamics Specialist Conference, Pittsburgh, PA, August 9-13.

Pace, Scott. 2009. Statement before the House Subcommittee on Space and Aeronautics, Committee on Science and Technology, April 28. http://gop.science.house.gov/Media/hearings/space09/april28/pace.pdf (accessed February 22, 2010).

Perek, Lubos. 1991. Space Debris and the World Community. *Space Policy* 7: 9-12.

Sheldon, John B. 2005. "Reasoning by Strategic Analogy: Classical Strategic Thought and the Foundations of a Theory of a Space Power." *PhD diss.,* University of Reading.

U.S. Department of Defense. 1999. Department of Defense Space Policy. http://www.au.af.mil/au/awc/awcgate/dod-spc/dodspcpolicy99.pdf (accessed June 2, 2010).

Wolf, Jim. 2009. Iridium says in dark before orbital crash. *Reuters*, February 12. http://www.reuters.com/article/newsMaps/idUSN1244243120090212?sp=true (accessed November 14, 2009).

Wright, David. 2009. *Colliding Satellites: Consequences and Implications*. Union of Concerned Scientists. http://www.ucsusa.org/assets/documents/nwgs/SatelliteCollision-2-12-09.pdf (accessed November 14, 2009).

—. 2007. Space Debris. *Physics Today* 60: 35-40.