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A Liability and Insurance Regime for Space Debris Mitigation

Ting Wang

Program on Science and Global Security, Princeton University, Princeton, NJ, USA

ABSTRACT
Concerns about the threat that space debris pose to satellites are expected to increase as the number of mostly non-maneuverable microsatellites in low-Earth orbit grows. International guidelines developed to mitigate the risk from space debris are frequently not followed, however, and may not be able to cope with the dramatic growth expected in the number of satellites. Moreover, the current legal framework is unable to determine who is liable for losses in an on-orbital collision. A space surveillance data-sharing committee is proposed to solve this liability problem. Under the proposed liability rules, satellite operators would be liable for the debris they create and insurance companies would cover such a risk, creating a new financial incentive for operators to adopt space debris mitigation guidelines.

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Introduction

Space debris is becoming a significant threat to satellites. Two collisions have already occurred between active satellites and trackable pieces of debris: The French satellite Cerise was hit by a piece of the Ariane rocket in 1996, and the U.S. Iridium-33 satellite collided with the defunct Russian Cosmos-2251 in February 2009.

More importantly, space could soon be dominated by microsatellites. While currently there are only about 1,000 active satellites in space, 2,000–2,750 microsatellites are projected to be launched in the next six years.[1] As most microsatellites do not have maneuver capability, their presence could pose a significant problem in the future.

International efforts to deal with this problem have resulted in the establishment of the Inter-Agency Space Debris Coordination Committee (IADC).[2] The committee worked to develop a set of international space debris mitigation guidelines, first published in October 2002 and released in the final form in 2007.[3] Based on the guidelines, the United Nations Committee on the Peaceful Uses of Outer Space (UNCOPUOS) published "Long-Term Sustainability Guidelines" in 2010.[4] Although the guidelines have helped reduce some types of debris, such as fragments from rocket upstage breakup, there is no mechanism to enforce compliance with the

CONTACT Ting Wang mr.wangting@gmail.com 221 Nassau Street, Princeton, NJ 08540, USA.
Color versions of one or more of the figures in the article can be found online at www.tandfonline.com/gsgs.

guidelines, and some guidelines are frequently not followed, such as end-life disposal of satellites in LEO.

The UNCOPUOS guidelines also do not address the issue of liability. If a fragment strikes a satellite, the owner of the satellite is unlikely to get compensation from the country or company that created the fragment. Solving the liability problem may offer a path to dealing with the debris problem. If satellite operators would be held liable for the debris they created, there would be a financial incentive for them to adopt debris mitigation guidelines. This article proposes setting up a space surveillance data sharing committee to solve the liability problem.

Problems of the current regime

Space debris mitigation

Concerns in the early 1990s about the growth of space debris, largely due to the breakup of orbiting rocket bodies, led to the development of the IADC guidelines. The guidelines, which regulate the activities of spacecraft operators, give four broad directions to reduce the debris population: "Limit Debris Released during Normal Operations"; "Minimize the Potential for On-Orbit Breakups"; "Post Mission Disposal"; and "Prevention of On-Orbit Collisions." In detail, the guidelines suggest that: [5]

- Intentional destructions, which will generate long-lived orbital debris, should not be planned or conducted.
- Spacecraft that have terminated their mission should be maneuvered far enough away from GEO.
- Space systems that are terminating their operational phases (in LEO), should be de-orbited or where appropriate maneuvered into an orbit with a reduced lifetime [the guidelines recommend 25 years as the appropriate lifetime limit].
- If reliable orbital data is available, avoidance maneuvers for spacecraft and co-ordination of launch windows may be considered if the collision risk is not considered negligible.

The IADC guidelines have been partly successful. For example, The U.S. Federal Communications Commission (FCC) requires all U.S. geostationary satellites launched after March 18, 2002 to be committed to maneuver away from GEO.[6] The U.S. National Oceanic and Atmospheric Administration requires private companies to provide post-mission disposition plan when they apply for licenses for remote sensing satellites. NASA and U.S. Air Force also endorsed the guidelines.[7, 8]

However, since the IADC guidelines are voluntary, there is no penalty for nations or organizations that do not comply with them. In particular, end-life disposal of satellites in LEO is poorly implemented.

Many satellites, not just low-cost microsatellites, do not have maneuver capacity.[9] According to our calculation, based on orbital data published by the Joint Space Operations Center (JSpOC) of U.S. Air Force, roughly 30% of LEO active satellites did not perform any maneuvers between 2011 and 2013.[10]

Moreover, operators of maneuverable satellites could be reluctant to perform end-life deorbit. Unlike GEO satellites, for which running out of fuel means end of mission even if their components are working well, LEO satellites may still function after running out of fuel, especially if they do not have to maintain their orbits. Besides, it is costly to deorbit a LEO satellite, as the amount of propellant required to complete the deorbiting maneuver can be as high as 11% of the total mass of the satellite for a 1,500 km orbit.[11] Accordingly, the compliance with the guidelines requirement to place a satellite in an orbit with no more than 25 years lifetime is rather low. Unfortunately, LEO is the place where on-orbit collisions are most likely to happen, as where 99.9% of conjunctions occur on LEO.[12]

Holger Krag et al. calculated the orbital lifetime of satellites retired in 2010–2011, and found that only 17 of 47 LEO satellites complied with the 25-year rule.[13] We checked the orbit of 1,898 satellites launched after 1990, and found that only 12 LEO satellites are likely to conduct end-life maneuvers to satisfy the 25-year rule. Four of them belong to France, three are owned by the United States. Japan, United Kingdom, Nigeria, Algeria, and ESA have one satellite each. Russia and China, which launched 649 and 151 LEO satellites, did not conduct any maneuvers to comply with the 25-year rule. Since the IADC guidelines were published in 2002, the satellites developed after 2002 may be expected to be more likely to adopt the guidelines. However, only five satellites launched after 2002 conducted end-life maneuver, while more than a hundred satellites launched after 2002 were dead and left in an orbit with more than 25 years lifetime.

Making satellite operators perform collision avoidance is another problem. While the reason for the IADC to encourage collision-avoidance maneuvers is debris mitigation, the incentive for satellite operators is to avoid financial losses. Owing to observation errors, the collision probability for each conjunction warning is usually less than 1%. Operators may see this as an acceptable risk, especially when their satellites are about to retire. However, the risk calculation may not be fully taking into account the consequences of a collision, which might create large number of debris.

Challenges from microsatellites

Microsatellites, generally taken to be satellites with mass smaller than 100 kg, present a new challenge for space debris mitigation. The number of microsatellites has grown rapidly in in recent years. There were 92 satellites with mass between 1 and 50 kg launched in 2013, more than triple the number of launches in the previous year. According to SpaceWork, 158 such satellites were launched in 2014, which represents 72% year-over-year growth[14]. SpaceWork projects that 2,000–2,750 microsatellites will be launched in the next six years. Figure 1 shows the number of satellites deployed in low earth orbits. Even if only half of the satellites projected by SpaceWork are actually launched, i.e. no growth after 2014, there will still be approximately 200 satellites launched into LEO per year, more than any time in

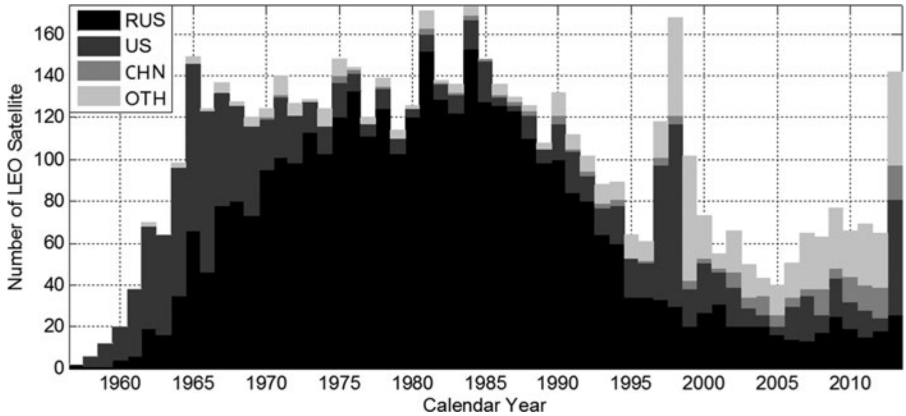

Figure 1. Number of satellites deployed in LEO (1957–2013).

history, and three fourths of them are microsatellites. The space debris population could increase much more rapidly than previously thought.

Currently, most microsatellites are not the primary payload of a rocket, and are typically deployed into an orbit close to the primary payload. While the primary payload has maneuver capability and could de-orbit after the satellite retired, most microsatellites, if not all, are unmaneuverable. Microsatellites tend to have shorter orbital lifetime due to their inherently higher area-to-mass ratio. However, there are microsatellites with orbit lifetime longer than 25 years. Figure 2 provides the perigee altitude distribution of active microsatellites ($<$100 kg) based on the UCS Database (Updated at 1 September 2015). According to the figure, almost 23% of active microsatellites have a perigee greater than 750 km. These satellites are likely to have orbital lifetimes greater than 25 years. Giving the increasing number of

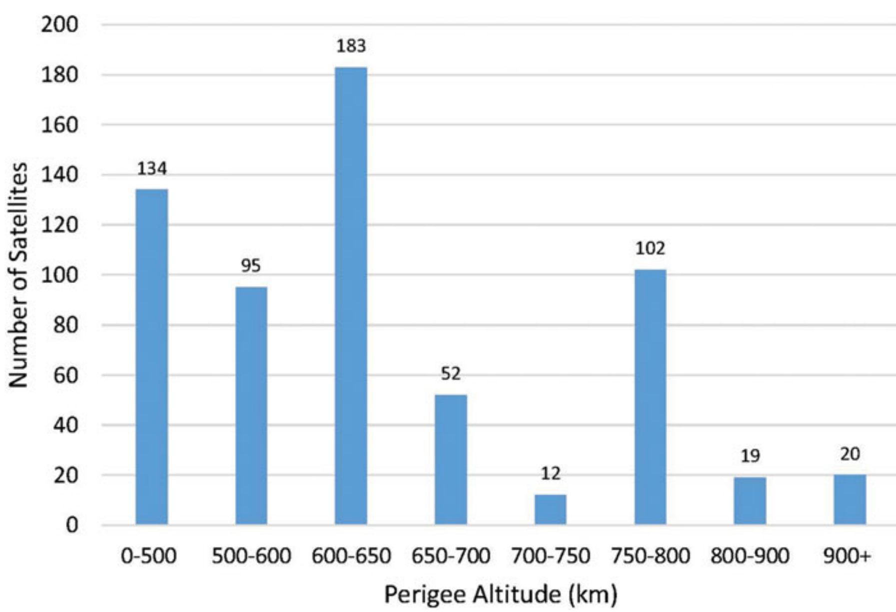

Figure 2. Perigee distribution of microsatellites.

microsatellites to be deployed in the future, even a 5% non-compliance rate could result in adding more than ten satellites each year, significantly increasing the probability of a collision.[15]

The IADC guidelines were developed at a time when microsatellites were still largely only on paper. The microsatellite boom would add 2,000–2,500 intact objects in space, which has the potential of undoing the progress that would be achieved by full IADC guidelines compliance.[16] It is therefore not clear if the guidelines remain suitable for the new environment, in which microsatellites dominate LEO.

Liability for on-orbit collisions

The question of liability for on-orbit collisions gained attention after the Iridium-Cosmos-2251 collision. Collision in space is considered in the current legal regime. Article VII of the Outer Space Treaty states that,

> Each State Party to the Treaty that launches or procures the launching of an object into outer space, including the Moon and other celestial bodies, and each State Party from whose territory or facility an object is launched, is internationally liable for damage to another State Party to the Treaty or to its natural or juridical persons by such object or its component parts on the Earth, in air space or in outer space, including the Moon and other celestial bodies.

One of the challenges in the current regime is that there is no clear definition of "fault." In the Iridium-Cosmos case, one may argue that the United States did not warn Iridium operators of the possible collisions, therefore it is at fault in this case.[17] However, even if the United States provided a warning, the operators would have received an estimate of a probability of a collision, which could be less than 1/10,000. It is still possible that Iridium would not have performed a collision avoidance maneuver because the collision probability could be too low to trigger it. According to the JSpOC orbital data, the minimum distance between Iridium-33 and Cosmos-2251 was estimated to be about 800 m around the collision moment. In the past, Iridium-33 passed within similar distance of a large number of other satellites. Indeed, if each conjunction with less than 1 km distance were to trigger a maneuver, Iridium 33 would have required 29 maneuvers in 2008.

Even for those cases in which "fault" is clear, implementing the treaties might be still difficult. Consider this example: a Russian fragment, created by an anti-satellite (ASAT) test, hits an unmaneuverable active U.S. satellite. Even presuming there is a consensus that the owner of the fragment is at fault, the problem remains how to ascertain that the fragment belongs to Russia.

For fragments that were produced more than one year in the past, it is difficult to prove with high probability that a given fragment was created in a specific breakup event (such as an ASAT test). At the same time, it appears to be relatively easy to create pseudo data showing the fragment resulted from other breakups. Although the United States has already provided the source of each object in its JSpOC catalog, it does not provide enough data on how the source of fragment is determined.

Due to the lack of transparency, it would be difficult to use this database as proof in assigning liability.

Another practical problem is how to determine compensation. Article XII of the Liability Convention states that the compensation should be determined "in order to provide such reparation in respect of the damage as will restore the person, natural or juridical, State or international organization on whose behalf the claim is presented to the condition which would have existed if the damage had not occurred."

However, it is not a settled or clear whether lost earnings should be compensated in the current liability system. When the legal system was established, satellites were mainly used by governments. However, space is being commercialized. The majority of satellites in GEO are already commercial satellites. While governments remain the largest players in LEO, according to the UCS Satellite Database, 50% (327/653) of satellites in LEO today are commercial or civilian satellites.

More importantly, the "market value" of a satellite could also be quite different from the cost to replace the satellite. For example, it took roughly 7 billion dollars to build the Iridium system. However, the system was sold at a price of 35 million dollars several years later.[18]

Summing up, controlling the amount of space debris requires countries, organizations, and companies to implement the IADC guidelines. However, the lack of financial penalties for failing to comply with these guidelines discourages satellite operators from implementing expensive operations, such as end-life maneuvers in LEO. Because of their knowledge of the details of the satellite operations, companies can easily find a "legitimate" reason for not implementing the IADC guidelines and it is difficult to challenge them.

The vague terms in the current space debris regime make it hard to determine the liability for an on-orbit collision. Since creating space debris does not bring any penalty, satellite owners may seek to avoid implementing costly mitigation guidelines.

Amendment of the current regime

Solving the on-orbit collision liability problem may offer a key to persuading nations, organizations, and companies to implement the IADC guidelines. Making operators liable for the damage caused by their satellites may provide one way of doing so.

The current regime already provides the legal basis to determine liability. The essence of Article VII of the Outer Space Treaty and Article III of the Liability Convention[19] is to create a rule of fault-based liability, i.e., if one country is determined to be at fault, and that fault causes damage to another country or organization's assets, the country at fault is liable for the losses.

However, to determine the liability for an on-orbit collision, the meaning in the treaties of the terms "fault" and "damage" should be clear. We proposed that countries or organizations who have unmaneuverable objects should be considered to be at "fault" if their objects collide with other functional objects, or their objects cause functional objects to use additional fuel to perform a collision-avoidance maneuver. If the satellite operator does not perform the necessary actions for collision avoidance to avoid the collision, the satellite operator is at "fault."

The "damage" includes the physical damage caused by a collision, as well as financial loss in performing the collision avoidance maneuver.

In practice, several questions still have to be answered:

1. Who is liable for a space object?
2. How to define a functional space object?
3. How to calculate damage?
4. How to define a potential collision?
5. How to define the mandatory requirements for collision avoidance?

Currently, there is no international regime that requires registering space debris. The United States and Russia, using their own space surveillance systems, have identified the source for more than 10,000 fragments. Unfortunately, as already described, these national catalogs could not be used as proof in a legal proceeding.

The current system is also unable to answer questions 4 and 5. JSpOC began to provide satellite conjunction summary messages for many satellite operators after the Iridium-Cosmos collision.[20] However, space surveillance data only shows a probability of collision. There is no standard to tell when a collision avoidance maneuver should be performed.

Therefore, an independent organization is needed to identify the source of the fragments. This work should be done before a collision happens. At that time, there is no incentive for countries or companies to create pseudo-data that may mask the true origin of debris. The organization should also establish standards for collision avoidance, be able to find potential on-orbital collisions, and suggest to satellite operators that they perform orbital maneuvers.

One way to meet this need is by establishing a space surveillance data sharing committee to perform these missions. The committee could be a group of experts from major space fairing countries, including the United States, Russia, China, India, and European Union. Based on space surveillance data shared by nations, commercial satellite operators, and other NGOs, these experts could establish scientific standards to identify the source of space debris, predict orbital conjunctions and suggest to satellite operators that they should perform orbital maneuvers.

Each country, organization or satellite operator should pay an annual registration fee to the committee for their active satellites. The registration fee should be roughly equal to an insurance fee that covers the risk that satellites may collide with other space objects. The fee would be set according to the risk of collision, revenue from the satellite, maneuvering capability of the satellite, and willingness of the operator to share its orbital data.

The annual registration fee is designed to answer question 2 and 3. A satellite would be considered a functional space object as long as its annual registration fee is paid.

The committee would collect observation data from different places and provide collision avoidance instructions to the satellite operators. If the committee fails to inform them about the conjunctions, or provides the wrong maneuver schemes, the committee is liable for the losses to the countries or organizations and the debris created from the satellites.

Once an on-orbit collision happens, the committee would determine liability of the collision. By joining the committee, countries should give up the right to use their private data to challenge the result provided by the committee. Liability for on-orbit collisions can be determined as follows.

In the case of a maneuverable satellite approaching an unmaneuverable space object, the owner of the unmaneuverable satellite is liable for the expense of the maneuver, and should reimburse the expense to the owner of the maneuverable satellite. If the operator of the maneuverable satellite chose not to implement the maneuver, which can be verified by space surveillance data, thus causing a collision, the operator is liable for its own losses and the debris created in the collision from the maneuverable satellite. The owner of the unmaneuverable space object is liable for its own loss and the debris created from its space object.

It may be argued that the owner of the maneuverable object should bear the full cost of the failure to conduct a maneuver. However, the unmaneuverable satellite is at fault for being unmaneuverable, which causes potential threats to the space environment and is discouraged in the proposed regime. The cost of orbital maneuver can be determined by the fuel used in maneuver and revenue/lifetime losses due to the maneuver. The cost can range from hundreds of dollars to half a million dollars depending on the mission.[21]

In the event that a conjunction is found between two maneuverable satellites, satellite operators should share the expense for the maneuvers. If one operator promises to implement a maneuver, but fails to do so, the operator is liable for the losses and all the fragments created in the event of a collision. If none of the operators is willing to implement a maneuver, and a collision happens, each side is liable for loss of their own side, and the debris created from their own side.[22]

In the case that a conjunction is found between two unmaneuverable space objects, each party is liable for the loss of their own satellite and for the debris created by it.

It is worth noting that, according to Article IX[23] of the Liability Convention together with Article VII of the Outer Space Treaty, states are liable for the damage caused by their non-governmental entities, which include private companies. Therefore, victims of damage cannot claim compensation directly from the satellite operator but the operator's country.

To hedge the risk, nations would ideally establish domestic laws to require satellite operators to buy liability insurance to cover the risk of legal compensation owed for collisions of their space objects with other satellites. The insurance could be provided by the government or private insurance companies. The same logic is used in compulsory automobile liability insurance and other liability insurances. Liability insurance already exists in the space industry, in the form of third-party liability and government property insurance to protect launch service providers and their customers in the event of public injury or government property damage, respectively, caused by launch or mission failure.[24] The liability insurance fee can be determined using a Monte Carlo calculation method similar to that already used in predicting the future space debris environment.[25]

Feasibility of the regime

The regime only works if the major space powers are willing to share their space surveillance data, and countries, organizations, and companies are interested in participating in the regime. Issues raised by national security concerns, and cost-benefit analysis for different countries and companies are discussed below.

Is sharing of space surveillance data possible?

Sharing space surveillance data would improve space situation awareness (SSA) capability worldwide and help decrease collision risk of all satellites. However, space surveillance systems are usually controlled by the military, and it is normally unwilling to share data. Although the Joint Space Operations Center (JSpOC) of the U.S. Air Force has provided low-accuracy orbits for 15,000 space objects for many years, it is still unwilling to share its higher precision data. Russia and China currently do not provide their catalog publicly.

One of the major concerns in the military is related to a potential disclosure of information about classified satellites and the capacity of space surveillance systems. To ease the concern about classified satellites, the committee would not require countries to register every satellite. Unregistered satellites will be treated as dysfunctional space objects. Since the United States, Russia, and China have independent space surveillance systems, it will not be difficult to identify the source of the "dysfunctional space objects."

To address the concern that participation in the regime might lead to disclosure of details of a country's space surveillance system, the committee could establish a specific format for data with an agreed-on level of accuracy. Countries could add noises to their high accuracy data to reach that accuracy level. In the future, as mutual trust is built, and space surveillance data are no longer regarded as highly sensitive information, countries may be willing to share data that are more accurate.

To encourage data sharing, the committee could give discounts on the annual registration fee to those who provide orbital data of their own satellites. The committee could also give another discount to the satellite operators whose countries provide the space surveillance data. The regime would also provide an incentive for countries to share data in those cases when they want to prove they are not liable for the fragments.

Therefore, sharing space surveillance data could be difficult to initiate, but not necessarily impossible. Already, in addition to the publicly available catalog data, JSpOC has legal agreements to share more data with 16 commercial entities in order to avoid on-orbit collision,[26] and the public JSpoC portal was updated recently in order to provide more data.

Actually, even if the United States is the only country willing to share the data, the proposed system still can work. In the current system, due to lack of transparency, U.S. attribution can be contested as biased. In the proposed system, the United States would have to provide more data and information on how it made attribution, and the sources of fragments will be determined by rules set by scientists from all space faring countries. Therefore, an attribution would be based on an international consensus, rather than on internal U.S. determination.

Cost-benefit analysis for nations and organizations

The attitudes of possible stakeholders (nations as well as organizations) toward the proposed amendment may depend on their number of active satellites and dysfunctional space objects.

The United States has created the second largest amount of dysfunctional satellites and space debris in history. In the proposed amendment, the United Sates would be required to take liabilities for the losses caused by these objects. However, the United Sates also has almost as many active satellites as rest of world put together and potentially suffers the most severe consequences if the space debris problem goes out of control. Several U.S. satellites are believed to have been the victim of space debris. Therefore, the United States was a major advocate for the IADC guidelines, and it has officially adopted the IADC guidelines by establishing corresponding domestic laws.

European countries, Japan, and most of the developing countries have only a small number of dysfunctional objects. Since they do not have the historical burden, it is clearly in their interests to join the regime.

China and Russia have a lot of fragments, but a relatively small number of functional satellites. They could be the major obstacles for the regime. However, controlling space debris growth is in their interests. Negotiations with these two countries are inevitable. The regime might be made more attractive for them if it establishes an "amnesty date," so countries would not be liable for breakup debris created before that date. Exempting the liability of breakup debris might be practicable as well, since, technically, it is hard to "prove" the source of the debris, and creating space debris was not considered wrong 30 years ago.

The proposed regime is essentially a regulatory and market solution to the expected space debris problem. It does not pose any political or security challenge to space-faring countries. Compared to other methods, such as actively removing massive space objects, the proposed method could be one of the most cost effective ways to deal with the debris problem.

If a major space-faring country, such as United States, is willing to take the initiative, other space-faring countries could join. While many countries have satellites, there are only eight countries/organizations capable of launching satellites. Iran, Israel and North Korea are not included, since they do not provide commercial launch services for other countries. If these countries/organizations join the new regime, they are able to force the entire world to join the regime by not providing launch service to countries that are unwilling to join the regime. Actually, countries without launch capability are unlikely to have many dysfunctional objects in space, joining the committee will be more likely to bring them economic benefits.

Cost-benefit analysis for private companies

Private satellite operators in the current regime pay a property insurance fee to protect their satellites. They also pay for collision avoidance. In the proposed regime, satellite operators will pay an annual registration fee and collision liability insurance for their satellites. The annual registration fee is designed to be close to the property insurance expense from collision risk posed by space debris. By paying the annual registration fee, operators could reduce the property insurance expense. That is because if the satellite were destroyed by fragment, the cost will be covered by the liable country/organization rather than by the insurance company. In addition, expenses for collision avoidance maneuvers can be reimbursed.

Collision liability insurance is the real additional financial burden. However, for companies that already obeyed the IADC guidelines, the liability insurance would be very low. Their dead satellites will decay quickly or stay at an orbit with no chance of colliding with active satellites. Even if these satellites collide with other objects, the debris created in the collision will also have very short lifetime. More importantly, these companies will not be at disadvantage when competing with a company that ignores the IADC guidelines.

In the long term, since the proposed regime encourages space debris mitigation, the amount of space debris will increase at a much slower rate, thus reducing the costs for all satellite operators.

Establishing and maintaining the data sharing committee

It will be very difficult for nations to agree on a new organization dedicated to on-orbit collisions that occur very rarely.

However, although collisions in space are rare, collision avoidance maneuvers are routine tasks for satellite operators. For example, 126 maneuvers were performed in 2010.[27] As the U.S. space surveillance system is upgraded to add 200,000 objects, more maneuvers are expected.[28] The proposed organization will provide information, guidance, and standards to the satellite operators. More importantly, it would establish a vehicle for compensation for those maneuvers. The agency would not only determine the liability of on-orbit collisions, but also has a role in space traffic management. The costs of maintaining the committee are a separate concern.

The annual registration fee would be several thousand dollars for a typical $100 million satellite in LEO. With roughly 600 operational satellites in LEO, it would not be difficult to collect one million dollars each year if all satellites are registered.[29]

The operation cost for the committee would be very small. The technologies for determining debris source, detecting possible conjunctions and planning for orbital maneuver are already well developed. The hardest task would be to establish standardized procedures to deal with these issues. However, once the standard procedures were established, most of the work could be done with minimal cost.

Conclusion

The space debris problem is often described as an example of the tragedy of the commons: everyone works for his short-term interests, without regard for the shared environment or their own long-term interests.[30] The current regime, which is based on voluntary guidelines, shows that moral incentives do not seem to solve the problem, especially in low earth orbits. The growing number of microsatellites is likely to make things worse. Although companies can buy the insurance to hedge the risk of being hit by space debris, that is unlikely to influence the growth in the amount of space debris.

However, there are unique properties of the space debris problem: it is possible to know exactly who caused a collision and who created the resulting fragment. Moreover, property losses that occur in space can be easily estimated. These features make it possible to determine the liability for collisions and the loss in the collisions.

In the proposed arrangement, the liability for on-orbit collisions can be determined by sharing space surveillance data. Once the liability is determined, operators who lose their satellites can get compensation. The proposed regime therefore would provide a strong financial incentive for countries and companies to comply with the debris-mitigation guidelines.

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Supplemental material

Supplemental data for this article can be accessed on the publisher's website and the website of the journal.

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9. It is possible to deploy foil panels on a satellite to increase atmosphere drag, so that the satellite can deorbit much more quickly. However, that would increase the cost of mission, and more importantly, the additional foil panel would increase collision risk with other spacecraft in the short term. Given that relative speed in space is 10km/s, even a foil panel could disable a satellite.
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11. Inter-Agency Space Debris Coordination Committee, "Space Debris Handbook," NASDA-CRT-98006, 1998.
12. We calculate conjunctions of U.S space track catalog against itself from 1 Jan 1998 to 1 Aug 2008. The critical distance is 5 km. 8,430,372 conjunctions are found, where more than 99.9 % of conjunctions (8,423,342) are in low earth orbits.
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15. Presume there are 400 microsatellites launched every year, 2.5% of which have a lifetime greater than 50 years, 2.5% with a lifetime between 25 years and 50 years, 30% with a lifetime between 10 years and 25 years, 25% with a lifetime between 3 years and 10 years, and 40% with a lifetime between 1 year and 3 years. There will be roughly 3,000 microsatellite in space after 50 years $[(2.5\% * 400 * 50) + (2.5\% * 400 * 25) + (30\% * 400 * 10) + (25\% * 400 * 3) + (40\% * 400 * 1) = 2{,}410)]$. This might not seem to be a large number, considering that there are 17,000 cataloged objects already in low earth orbits. However, only 3,500 out of 17,000 objects are intact objects and the rest are fragments. The mass of a fragment is usually smaller than 1 kg. Even if a fragment collides with an intact object, it might not result in the total breakup of the satellite. The collision between microsatellites and intact objects, however, could be catastrophic, in which the intact object will totally breakup. Adding 2,500 microsatellites, the probability of catastrophic collisions (a collision in which satellites are totally breakup) of existence intact objects in low earth orbit would approximately increase 70%.
16. According to a calculation based on NASA LEGEND model, number of objects ($>$ 10 cm) in LEO will increase by roughly 2,000 over next 50 years and 11,000 over next 100 years, if satellites are launched at the current rate and space debris mitigation guidelines are not complied with. If 90% of satellites and rockets comply with the 25-year rule, and launched at the current rate, number of objects ($>$ 10 cm) in LEO will be roughly the same over next 50 years

and increase by 3,000 over next 100 years. (Liou, J.-C. "An Active Debris Removal Parametric Study for LEO Environment Remediation." *Advances in Space Research*, 47 (2011): 1865–76.) Therefore, applying IADC guidelines would reduce by 2,000 objects over the next 50 years and 8,000 over the next 100 years. Presume there will be 400 microsatellites launched every year and half of them have a lifetime greater than 10 years. The number of microsatellite in LEO will be 2,000 in roughly a decade, and more than 2,500 over the next 50 years (see previous endnote). Consider possible collisions between intact objects and these microsatellites. More fragments would be produced. The microsatellite boom would essentially undo the progress made had the IADC guidelines been complied with.

17. RamS. Jakhu, "Iridium-Cosmos collision and its implications for space operations," *Yearbook on Space Policy* (2010): 254–275.
18. David Vernon, "A Heavenly Sign—The Iridium satellite story," *The Canberra Times*, 2007. http://www.davidvernon.net/David_Vernon/The_Canberra_Journal/Entries/2007/2/20_A_Heavenly_Sign_-_The_Iridium_satellite_story.html.
19. In the event of damage being caused elsewhere than on the surface of the Earth to a space object of one launching State or to persons or property on board such a space object by a space object of another launching State, the latter shall be liable only if the damage is due to its fault, or the fault of persons for whom it is responsibles.
20. D. Bird, "Sharing Space Situational Awareness Data," Proceedings of the Advanced Maui Optical and Space Surveillance Technologies Conference, in Wailea (1—4 September 2010, Maui, Hawaii).
21. The cost of building International space station (ISS) is $200 billion and the design lifetime of ISS is 30 years. If one assumes a collision avoidance would make ISS inoperable for an hour, the lifetime loss of ISS would be 760,000 dollars.
22. Satellites travel at different orbits. The fragments created in the breakup travel at orbits close to their parent satellites' orbits. Technically, it is not difficult to trace the source of the fragments.
23. A claim for compensation for damage shall be presented to a launching State through diplomatic channels. If a State does not maintain diplomatic relations with the launching State, it may request another State to present its claim to that launching State or otherwise represent its interests under this Convention. It may also present its claim through the Secretary-General of the United Nations, provided the claimant State and the launching State are both members of the United Nations.
24. U.S. Department of Transportation, and Federal Aviation Administration, "Liability Risk-Sharing Regime for U.S. Commercial Space Transportation: Study and Analysis," April 2002.
25. The straightforward way to estimate the insurance fee is the Monte Carlo method. The first step is to set up a database containing information, including size, orbit, and value, for all the artificial objects. The orbits of each object are then propagated forward in time. Collisions between the satellite and other objects are calculated and the potential damages are estimated. If the satellite collides with other objects, the fragments created in the collision can be estimated by the standard satellite breakup model. Orbits of these fragments are computed and the potential damages would be evaluated. The process would be executed tens of times to get an average result.
26. Jeff Foust, "A New Eye in the Sky to Keep an Eye on the Sky," *The Space Review*, 10 (2010).
27. Micah Zenko, "The danger of space debris," Fareed Zakaria GPS, Global Public Square Blogs, http://globalpublicsquare.blogs.cnn.com/?s=The+danger+of+space+debris.
28. Christian Davenport, "Lockheed Martin wins 'space fence' contract," *The Washington Post*, 2 June 2014, http://www.washingtonpost.com/business/economy/lockheed-martin-wins-space-fence-contract/2014/06/02/f302413e-ea97-11e3-93d2-edd4be1f5d9e_story.html.
29. The annual registration should be lower than the potential financial loss caused by the orbital debris. The probability of a satellite hit by orbit can be estimated as follows. There have been

two active satellites struck by cataloged objects in last 50 years. Therefore, the collision rate is roughly once every 25 years. There are roughly 400 large operational satellites in low-Earth orbit. Presume the collision rate of every satellite is the same. Then the collision rate for a satellite each year is one in ten thousands (1/25/400). Therefore, the annual registration fee for a ten million dollar satellite would be no more than 10,000 dollars.

30. Garrett Hardin, "The Tragedy of the Commons," *Science*, 162 (1968): 1243–1248.