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IS IT TIME FOR SPACE DEBRIS REDUCTION CAPABILITIES?

by

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14. ABSTRACT

For over 50 years, space-faring nations have launched objects into space, resulting in the significant accumulation of debris. The amount of launches and debris-causing events outpaces the current removal rates for debris in the protected regions of Low Earth and Geosynchronous Orbits. Thus, it appears the space debris problem is increasing. Currently, debris must be larger than 10-cm in diameter to be tracked reliably. Existing treaties are outdated and in need of revision to include space debris and enforcement. Given the increasing amount of debris in space, it is time to assess whether reduction/removal capabilities are required to resolve the problem. The research method used for this paper is the problem/solution method. An assessment of risk will convey the probability and consequence of a collision. An analysis of existing treaties convey areas of weakness in terms of controlling the space debris problem. Mitigation and protection measures are assessed for effectiveness to determine if debris- removing capabilities are needed. Finally, an analysis of potential debris-removing solutions determine technical feasibility and cost effectiveness. Ultimately, we need to be more proactive in fixing the near-term problem instilling the discipline among space-faring nations to control the accumulation of debris before we can look to a long-term, debris-removing solution when searching for ways to protect the space environment in the future.

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Abstract

For over 50 years, space-faring nations have launched objects into space, resulting in the significant accumulation of debris. The amount of launches and debris-causing events outpaces the current removal rates for debris in the protected regions of Low Earth and Geosynchronous Orbits. Thus, it appears the space debris problem is increasing. Currently, debris must be larger than 10-cm in diameter to be tracked reliably. Existing treaties are outdated and in need of revision to include space debris and enforcement. Given the increasing amount of debris in space, it is time to assess whether reduction/removal capabilities are required to resolve the problem. The research method used for this paper is the problem/solution method. An assessment of risk will convey the probability and consequence of a collision. An analysis of existing treaties convey areas of weakness in terms of controlling the space debris problem. Mitigation and protection measures are assessed for effectiveness to determine if debris-removing capabilities are needed. Finally, an analysis of potential debris-removing solutions determine technical feasibility and cost effectiveness. Ultimately, we need to be more proactive in fixing the near-term problem instilling the discipline among space-faring nations to control the accumulation of debris before we can look to a long-term, debris-removing solution when searching for ways to protect the space environment in the future.

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PART ONE

Introduction

For over 50 years, space-faring nations have launched objects into space, resulting in the significant accumulation of debris. This debris, consisting of spent rocket boosters, abandoned satellites, nuts, bolts, satellite thermal blankets, etc, continues to be a growing threat to existing and future spacecraft. The U.S. Space Surveillance Network currently tracks over 17,300 man-made objects (ten centimeters (cm) or larger), 300,000 objects between one and ten cm in diameter, and billions more even smaller.[1] "Between June and December 2006, there occurred eight satellite break-ups for a rate of one per month."[2] Compounding this trend is the anti-satellite test (ASAT) China performed on 11 January 2007 (which resulted in thousands more pieces of debris thrown into a range of orbits of varying altitudes).[3] Thus, it appears the space debris problem is increasing.

With this increase in orbital debris, we have seen an increased risk of collision. Most debris resides in low earth orbit (the satellite freeway where bulk of imaging satellites reside) and geostationary orbit (the fixed point over equator providing widest coverage of Earth).[4] Spacecraft and orbital debris travelling in low earth orbits travel at high orbital velocities, therefore debris as small as 10 cm can hit with the same impact as a truck weighing 35,000 kilograms travelling up to 190 kilometers per hour.[5] July 24th, 1996 marked the 1st high-speed collision between two objects tracked in space (a French satellite and small piece of rocket debris).[6] It's believed that the increasing amount of debris in space will eventually result in areas inhospitable to space operations due to the increased risk of collision.

Current treaties may be outdated and in need of revision to include debris clauses. Although the international Outer Space Treaty (established in 1967) holds states responsible and liable for any damage due to launching objects into space, this liability really only applies to damage caused on the Earth's surface or aircraft in flight.[7] For damage occurring outside this area (i.e., space), liability does not occur unless the 'victim' state can provide proof that such damage occurred (and by who). This can be particularly challenging given the fact that even the smallest-sized debris can inflict damage and the originator of that debris will likely be unknown. Additionally, this treaty remains between nation-state actors, however the commercial industry are non-state actors that conduct space operations. In the attempt to clear up this ambiguity and establish some regulation, an Interagency Space-Debris Coordination Committee (IADC) has stood up to develop guidelines and recommendations for mitigating space debris. However, this is more of a 'gentlemen's handshake', there remains no authority for ensuring these guidelines are implemented and enforced.

Given the increasing amount of debris in space, the risk of collisions in the most utilized orbits, the limited accountability for damage due to space debris, and the voluntary nature of mitigating debris when conducting space operations, it may be time to expend dollars towards developing capability to reduce or eliminate the debris. Such capability may consist of graveyard boosts to higher orbits, electromagnetic tether systems, tape modules, capture capabilities or laser space propulsion. An analysis and discussion needs to assess the feasibility of developing this capability and the associated costs. This assessment will culminate in the determination of whether the problem has increased to the point where the risk of collision now outweighs the cost to remove debris from these orbits.

Research Thesis

Despite the increasing amount of space debris in LEO and GEO regions, the limited accountability for damage, and the voluntary nature of debris mitigation practices, the risk of debris colliding with spacecraft (manned and unmanned) does not outweigh the costs to develop capabilities to actively remove debris from orbit. It is not time to expend dollars towards developing solutions to move or eliminate space debris from orbit.

Research Method

The research method used for this paper is the problem/solution method. The problem examined is the accumulation of space debris in low-and geosynchronous earth orbits since the inception of space operations to present day (to include China's recent anti-satellite test). The risk collision was assessed by probability of occurrence and consequence (or impact) if a collision occurs. Space law and treaties were analyzed for relevance regarding the protection of the space environment from debris, and areas of weakness and lack of enforcement were highlighted to determine overall adequacy in relation to the space debris problem. Finally, this paper explored these challenges and potential solutions to mitigate or reduce this threat, to include estimated cost projections and feasibility analysis for developing these capabilities. In areas where cost data was not available, estimates were projected based on cost per kilogram and the mass of the capability.

PART TWO

Problem Definition

Since the Russians launched the first satellite in 1957, nations have launched objects into space and left behind a significant accumulation of debris. This space debris, defined as "all space objects non-functional and human-made" consists of spent rocket boosters, old satellites, nuts, bolts, garbage bags, a glove, etc. Anything and everything launched into space has left behind residual debris of varying size or shape and altitudes. Despite the vastness of space, debris has accumulated to the point where protection measures are required to maintain a hospitable space environment.

Orbits Most Impacted

Although there are a number of orbits of varying altitudes, inclinations, and eccentricities in which to launch spacecraft, there are only a few with parameters favorable to space operations. The orbit closest to the earth is Low Earth Orbit (LEO), which extends up to an altitude of 2000 km from the Earth's surface.[8] Within this altitude, orbits in the range of 150 to 800 km are most appealing to nation-states interested in remote sensing capabilities (photography, imaging, radar, etc). The close proximity to the Earth allows for images and photographs to be captured in greater detail than higher orbits. Spacecraft in this orbit travel at high velocities and can orbit 14 to 16 revolutions per day.[9] Furthermore, this is the least expensive orbit in which to launch satellites. For all these reasons, this orbit has become the most congested orbit in terms of spacecraft and the debris they generate. In this orbit, space debris can reach velocities around 25, 200 km/hour.[10] This can be concerning not only for satellites but also for manned spaceflight (which also takes place in this orbit).

Another highly desirable orbit is Geosynchronous Orbit (GEO), which is located at an altitude of 35,786 km over the Earth's equator.[11] Satellites in this orbit with a zero inclination and eccentricity have the appearance of being fixed or stationary with respect to the Earth, allowing them to "occupy a given orbital position related to the line of longitude above which they are stationed". This orbital position provides the widest coverage of the Earth, which is very attractive to nations when launching communications satellites. "A system of three equally spaced satellites can provide full coverage of the Earth, except for the polar regions where the elevation angle of the receiving antenna is very low."[12] As compared with LEO spacecraft, objects in this orbit have "lower relative velocities…[yet] debris at this altitude is still moving as fast as a bullet—about 1,800km/hr."[13] Although space is vast area, the LEO and GEO altitudes are highly sought after, making these orbits the prime real estate in which to conduct space operations.

Primary Space-Faring Actors

The launch of Sputnik set off a space arms race between the U.S. and Russia. Each country frantically tried to gain control of this final frontier by launching as many space objects (manned and unmanned) to achieve technological, political, economic, and military advantages over each other. "The use of the space environment [is] a source of national pride…it provides employment for citizens and acts as a wealth creator."[14] As seen in Figure 1, the list of major countries joining this race has now expanded to include China, Europe, France, Japan, India, and Israel (all have consistently demonstrated successful annual launches).

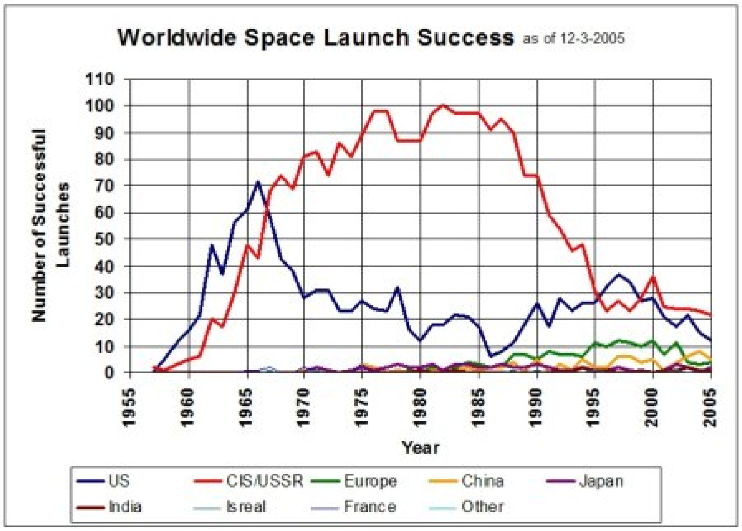

Figure 1: Worldwide Launches[15]

After 1987, the number of Russian launches significantly decreased largely due to the fall of communism; however, they still manage around 20 to 30 launches per year (with around 20 launches in 2008).[16] Although Figure 1 shows a decrease in the number of U.S. launches up to 2005, data that is more recent shows a slight increase (around 18 per year as of 2008).[17] One can also see a significant change in launch activity when looking at China's space capability. Although late to the space race (not entering until around 1990), China has consistently launched around five satellites per year up to 2005 (doubling this number in 2008).[18] Furthermore, they are the third country to conduct manned spaceflight successfully. Other countries planning to join the space race include Iran, Norway, Sudan, and New Zealand. However, nation-states are not the only actors interested in exploiting space. Commercial and industrial agencies view the space environment as an opportunity for sourcing businesses, contracts, and market shares. "The first samples of cremated human remains have been launched into temporary orbits, later reentering the atmosphere in a fiery reenactment of their cremation."[19] Government and civilian agencies view the space environment as an opportunity for activities such as scientific research, exploration, and weather forecasting. "Satellite industry's total world revenue reached $103 billion in 2004 and could exceed $158 billion by 2010."[20] Since Sputnik, some 50 nations have attempted around 4,700 launches, and almost 850 satellites are operational today.[21] Some studies show that even if nothing else launched into space from this point forward, the amount of debris would increase after 50 years due to collisions and breakups.[22]

Anti-Satellite (ASAT) Capabilities

Given all the advantages that space provides, it remains a highly sought after domain for many players. As such, it did not take long before nations grasped the fact that one nation's capability was another nation's vulnerability. Because of this fear, some counties became interested in developing and testing anti-satellite (ASAT) capabilities as a means of protection, which consists of either "kinetic kill vehicles, conventional explosives or direct energy weapons."[23] Many ASAT variants generate a significant amount of debris, but the kinetic kill vehicles are the worst. Before launch, this vehicle is loaded with debris fragments. When in orbit, it maneuvers alongside a satellite and then explodes (destroying the satellite and creating a mass debris cloud). As the leader in the space race, Russia was the first country to demonstrate ASAT capability. "Between 1963 and 1982 the Soviet Union tested a co-orbital ASAT system 23 times, including seven interceptions…generated more than 700 catalogued pieces of debris."[24] Although most of this debris has reentered the Earth's atmosphere, around 300 pieces are still tracked today. The U.S. has also demonstrated this capability on several occasions. During a kinetic energy test in 1985, an F-15 launched a missile at a Solwind satellite located in LEO, resulting in 285 pieces of debris (the last of which de-orbited in 2004).[25] Another demonstration occurred in February 2008 when a Standard Missile-3 was launched from an Aegis cruiser, destroying a U.S. satellite.[26] Because this particular test occurred at a much lower altitude, it did not result in any long-lasting debris in space. The most impacting demonstration in terms of debris generation was China's ASAT test conducted in January 2007. During this test, a Fengyun-1C spacecraft was destroyed by a "direct-ascent interceptor at a speed of approximately 9 km/s at an altitude near 850km."[27] This generated a debris cloud consisting of thousands more pieces of debris thrown into a range of orbits of varying altitudes. Approximately 2600 pieces of debris are larger than 10 cm, however NASA estimates an additional 150,000 pieces of debris exists (down to 1-cm).[28] This test caused "the worst satellite fragmentation in the history of the space age."[29] What remains unknown is how many more countries will attempt ASAT tests. Given China's defensive posture and fear of transparency, it is very possible that they could perform follow-on tests in the attempt to prevent other countries from gaining information on their activities via space. Satellite breakup rates could increase to the point where significant debris clouds exist in key orbits that result in inhospitable areas.

Tracking and Space Surveillance Capabilities

With all the increased activities in space, it has become critical that debris is detected and tracked to protect the spacecraft. Depending on the altitude and radar cross-section of the debris, our detection and tracking capabilities are limited to the LEO and GEO orbits (with GEO being the most challenging due to the altitude), which isn't necessarily bad given that these are the most congested orbits. Debris is tracked using a combination of optical telescopes (most effective for objects in GEO) and radar (most effective for objects in LEO). Currently, an international space surveillance system does not exist. However, several countries have established their own systems to track objects, and in some cases have been willing to share the data. The countries most involved with tracking are the United States, United Kingdom, Germany, and France. The U.S. Space Surveillance Network (SSN) is the leading mechanism for tracking debris and maintaining a catalogue of its location (which is critical information to satellite operators to provide early warning to conduct collision avoidance maneuvers or launch notifications). This system consists of around 30 radar and optical sensors, located at 16 sites around the world.[30] It is capable of reliably tracking objects that are ten centimeters or larger (currently tracking over 17,300 objects of this size).[31] "About seven percent are operational satellites, 15 percent are rocket bodies, and about 78 percent are fragmentation and inactive satellites."[32] However, there are over 300,000 objects between one and 10 cm in size, and billions more even smaller (especially in LEO).[33] Debris this small can only be observed using such systems as the Haystack Radar, which is a 37-meter telescope that can detect objects in LEO down to 5-mm in size if in the radar's line of sight.[34] To put all this into perspective, we currently track about 17,300 objects the size of a grapefruit or larger (10-cm), but can only observe anything smaller at a specific place and time at best. To complicate matters, the reliability of these systems is dependent on the space environment. Solar flares can cause these systems to lose objects for days. This can be concerning when planning launches and forecasting where the debris will be with respect to the launch trajectory. Given the increasing amount of debris (and debris creating activities such as ASAT tests), it is even more critical that our detection and tracking capabilities become more accurate, reliable and able to track debris less than 10 cm. Additionally, an international tracking system should be established and funded among all space-faring nations to share the burden of developing this capability.

PART THREE

Risk of Collision

Due to the ongoing space activities and generation of debris, as well as the tracking limitations and challenges that exist today, one must consider the risk of collision when conducting operations in today's space environment. Thus, risk is determined through examining the probability of the occurrence (i.e., the likelihood of a collision) and the consequence (i.e., the impact of a collision). This section will address both aspects when determining the overall risk to spacecraft, to include discussion of documented cases in which collisions have occurred.

Probability

In addition to the number of launches per year, another key factor contributing to the increasing amount of debris in space is the rate of satellite breakups. "Between October 2006 and October 2007, a total of 10 on-orbit fragmentations were detected…more than twice the long-term average of 4.5 fragmentations per year."[35] With the help of sophisticated probability models and software, scientists are able to predict the probability of collision with debris that is at least one to ten cm in diameter. The modeling and simulation activities rely on such variables as the spacecraft's cross-sectional area, flight path, and orbital altitude, as well as the size of debris object and relative speed. Using this model to assess the probability of a satellite colliding with a 10-cm sized object in LEO, it has been determined that "the average time between destructive collisions is about 10 years."[36] However, this analysis occurred before the PRC's 2007 ASAT test, which contributed to almost half of all known debris caused by satellite breakups that year and increased the catalogued debris population by 25 percent. With this test, the long-term probability of catastrophic collision with operational spacecraft near the area of incident increased up to 80 percent.[37] Furthermore, “the number of close approaches to the approximately 400 operational US satellites has doubled to almost 200 per week.”[38] However, NASA states that the probability of the shuttle colliding with a piece of debris (10 cm or larger) is extremely remote (one in 10,000 years) because of the altitude in which the shuttle orbits (approximately 400 km), the altitude in which they believe most debris resides (800 km), and the collision avoidance maneuvers that have been successful to date.[39] “On 27 August, 2008, the International Space Station conducted its first collision avoidance maneuver in five years to evade a piece of debris from [a] Russian spacecraft.”[40] NASA also attributes these explanations for the low occurrence of collisions with the International Space Station. The 2008 Space Report reaffirms “collisions between the ISS and very small pieces of debris are a daily but manageable problem.”[41]

Consequence

The consequence (or impact) of a collision with a spacecraft largely depends on the size of the debris and its orbital velocity or altitude. If a collision occurs with an object less than 1-mm (the size of a piece of pencil lead), the impact is low in terms of the satellite’s ability to function. However, repeated impacts with debris this small can erode sensitive surfaces (i.e., payload optics), causing some mission degradation over time (consider this normal wear and tear of a satellite). The impact increases when considering debris that is between 1-mm to 1-cm (up to the size of nickel). An aluminum sphere travelling at 22,320 miles per hour carries the equivalent amount of energy as bowling ball hitting at 300 miles/hour.[42] A collision could result in damage to (or loss of) the satellite if it pierces the critical components such as the unprotected fuel lines or the flight computer.[43] Debris that is 1 to 10-cm in diameter can have the same velocity as a truck weighing 35,000 kilograms travelling up to 190 kilometers per hour, piercing through most of the satellite's areas and causing mission degradation or loss.[44] Additionally, a collision of this size would result in more debris fragmentation to occur. "If a 10-cm debris fragment weighing 1 kg collides with a typical 1,200-kg spacecraft bus, over one million fragments 1 mm in size and larger can be created…results in formation of a debris cloud."[45] In terms of the altitude in which a collision occurs, the impact to the spacecraft can vary. "A 10-cm fragment in GEO has roughly the same damage potential as a 1-cm fragment in LEO [and] a 1-cm GEO fragment is equivalent to a 1-mm LEO fragment."[46]

Collision Risk Assessment

To put more simply, despite the 17,300 pieces of large debris that exist (greater than 10-cm in size), the probability of collision is lower because of the tracking and collision avoidance procedures that exist today. However, the consequence of collision with debris of this size is higher. Conversely, billions of debris less than 1-cm exist, thus the probability of collision is much higher due to inadequate tracking abilities. However, the consequence of a collision is with debris this size lower. Table 1 summarizes the risk of colliding with debris of varying sizes in terms of probability and consequence:

Debris Size	Probability	Consequence	Assessment
Less than 1 cm	High	Low	Moderate
1 to 10 cm	Medium	Medium	Moderate
Greater than 10 cm	Low	High	Moderate

Table 1: Risk Summary

The area of concern in terms of risk involves the 300,000 pieces of debris between 1 and 10 cm (too small to be tracked but large enough to cause some mission degradation or loss). Given the probability and consequences as described, the overall risk assessment for collision between a spacecraft and debris of varying sizes would be moderate.

PART 4

Space Law/Doctrine

Given the previous risk assessment, an analysis of existing space law and doctrine needs to take place to assess the relevance to today's space environment. There are five treaties with respect to space law, all of them written before the identification and understanding of the space debris problem became known. Currently, there is no legal (or internationally agreed upon) definition for space debris. Additionally, these treaties remain between the nation-state actors who were space-faring at the time, however more countries have joined the space arms race, to include non-state actors such as the commercial industry. This section will briefly describe each treaty's relation to mitigating space debris, as well as highlighting areas in which definition or enforcement is lacking.

1. Outer Space Treaty (1967)

Article III of this treaty stipulates that each launching nation-state is internationally responsible and liable for damage caused by its space object, whether the damage occurred on Earth, within air space, or outer space.[47] This liability pertains to the state that conducted the launch and the state that owns the payload (if conducted by different states), and appears to apply to all component parts caused by fragmentation. For damage occurring on Earth or during launch, it is quite easy to determine who is at fault and liable. However, for damage occurring outside this area (i.e., in space), it is very difficult to hold anyone liable unless the "victim" state can provide proof that damage occurred as a result of debris from another nation's fragmentation or spacecraft. This can be particularly challenging given the fact that debris less than 10-cm in size can inflict major damage and the originator of that debris will likely be unknown. The intent of Article IX is to protect the environment when conducting operations in space, but this protection is limited to the Earth. Nation-states shall "avoid harmful contamination and also adverse changes in the environment of the Earth resulting from the introduction of extraterrestrial matter."[48] This section does nothing to ensure the protection of space environment, which is particularly problematic with the development and employment of ASAT capabilities. Although Article IV prevents nation-states from placing or employing weapons of mass destruction in orbit (i.e., nuclear weapons), nothing prevents the use of conventional weapons from destroying spacecraft or satellites. This in turn creates more debris and increases the risk of certain orbits becoming inhospitable.

2. Rescue Agreement (1968)

The Agreement on the Rescue of Astronauts, the Return of Astronauts and the Return of Objects Launched into Outer Space (ARRA) stipulates that nations should help with the recovery efforts of space objects returned to Earth in the event that they landed outside the launching state's territory.[49] This treaty is most applicable to space objects and debris that reenter the Earth's atmosphere and land in another nation-state's territory. It does nothing to protect the space environment, therefore is not very helpful.

3. Conventional Liability (1972)

In 1972, the Convention on International Liability for Damage Caused by Space Objects treaty elaborated upon the liability principles established in the Outer Space Treaty. Article 1 defines a launching state, referring to "both a state which procures a launch and another should a launch physically occur within it territory" [50] Furthermore, it provides procedures for the settlement of claims through the stipulation that compensation be divided between states appropriately given the degree at fault. The problem with this treaty as written is that problems arise when both the debris and the damaged asset belong to the same state. This was the case when the French CERISE satellite that collided with a piece of debris from another French asset in 1996, severely damaging the satellite. Although liability was determined in this case, this collision created further debris. Thus, this liability only applies to damage to property in space but does nothing to hold nation-states liable for the protection the space environment.

4. Registration Convention (1976)

The ‘Convention on Registration of Objects Launched into Outer Space’ treaty stipulates the registration of objects launched in space. Each nation is responsible for establishing a national registry as well as sharing this information with the United Nations. Although this is helpful for determining liability if damage occurs due to a spacecraft, it does not appear sufficient to account for the identification or markings of the debris created during launch. Again, does not appear very helpful for protecting the space environment.

5. Moon Agreement (1979)

The ‘Agreement Governing the Activities of States on the Moon and Other Celestial Bodies’ treaty elaborates on the Outer Space Treaty by stipulating steps to prevent the contamination or disruption of the planetary environment. Article VII states measures should be taken to “prevent the disruption [caused] by introducing adverse changes in the environment [or] by its harmful contamination through the introduction of extra-environmental matter or otherwise.”[51] This treaty’s terminology is too vague, making it difficult to enforce. What is considered ‘disruptive’ or ‘harmful contamination’ when launching objects into space, and at what point is it considered to be either of these? Again, the international space-faring community has not agreed upon a legal definition for space debris so essentially, launching any space object into orbit could be harmful and disruptive.

PART FIVE

Mitigation Measures

In the attempt to clear up this ambiguity within the existing treaties and establish some regulation, an Inter-Agency Space Debris Coordination Committee (IADC) has stood up to develop guidelines and recommendations for mitigating space debris. The IADC is an international government forum consisting of major space-faring nations such as the U.S., Russia, China, and Europe (to name a few). The purpose of this committee is to advocate for continued research on space debris and ultimately recommend mitigation guidelines that are cost effective. The IADC identified specific regions in space that need protection from increased generation of space debris, specifically the LEO and GEO regions. "Any activity that takes place in outer space should be performed while recognizing the unique nature of the [LEO and GEO Region] to ensure their future safe and sustainable use."[52] In terms of the GEO region, the protection includes the altitude that is 200km above or below the GEO altitude of 35, 786 km (plus or minus 15 degrees latitude).[53] This section of the paper will briefly discuss the mitigation measures recommended by the IADC.

1. Limiting Debris released during normal operations[54]

This measure recommends that when developing satellites, all attempts be made (through improved satellite and booster design practices), to eliminate the release of debris when conducting operations in all orbits (or limit the amount of debris created if elimination is not possible). It discourages any project from continuing if they cannot verify (through analysis) that any debris fragmentation would be minimal or low probability of collision with existing spacecraft. Furthermore, it specifically stresses the importance of this analysis when considering the employment of tethered systems (in which case the analysis needs to include both intact and severed systems).[55]

2. Minimize the Potential for On-orbit Breakups[56]

This measure encourages the prevention of accidental satellite breakups (due to explosions or ruptures) while in orbit and when the mission is complete. During the satellite's design phase, it encourages each project to verify (again through analysis) that no probable failure mode exists that could lead to accidental break-ups. [57] If a failure is probable, then the program needs to mitigate the risk to reduce the probability of occurrence. While the satellite is operational, it encourages periodic monitoring and state of health checks to detect any malfunctioning components that could cause this breakup to occur as well as ensure the appropriate measures are in place to fix the problem or properly dispose the vehicle to a higher orbit. Furthermore, this step encourages the minimization of a breakup due to energy stored in the satellite. When approaching the end of its mission (and at a time when this can be accomplished safely to ensure the satellite is not damaged prematurely), the satellite will need to deplete any source that can cause an explosion or rupture (i.e., residual propellants). Items that cannot be depleted (i.e., batteries) should be de-activated or self contained to prevent erosion and the likelihood of material failure. Finally, this step discourages the occurrence of intentional destruction, stating "intentional breakups [self destruction, intentional collision, etc] should be [avoided or] conducted at sufficiently low altitudes so that orbital fragments are short lived."[58]

3. Post Mission Disposal[59]

This purpose of this measure is to encourage the safe employment of graveyard boosts or reentry back to Earth when the spacecraft has completed its mission. When a GEO satellite is no longer functional, it can take centuries before it de-orbits back to Earth, resulting in the accumulation of more debris in this highly used orbit. For this reason, the IADC encourages operators to boost these satellites to a graveyard orbit, located at least 235km outside the GEO altitude.[60] This step also encourages the proper disposal of the boosters and launch vehicles after separating from the payload. When a LEO spacecraft is no longer functional (to include the booster or launch vehicles that pass through this region to get to higher orbits), they encourage that they be deorbited back to Earth or into a lower orbit with a reduced lifetime (within 25 years if direct entry is not possible).[61]

4. ***Prevention of On-Orbit Collisions***[62]

The final measure foot stomps the need for increased vigilance and understanding of collision probabilities and development of avoidance measures when designing, launching and operating space systems. Specifically, it encourages the need to maintain situational awareness of updated orbital data and implement spacecraft protection measures (i.e., shielding and collision avoidance maneuvers) to reduce the probability of collision with other space assets or debris.

To sum up, the IADC has made great strides in uniting the international space community towards space debris mitigation. In 2007, the UN Committee on the Peaceful Uses of Outer Space (COPUOS) endorsed these guidelines however there remains no authority for ensuring their implementation or enforcement. "The member states pledged to implement these guidelines within their national licensing or other applicable mechanisms to the greatest extent feasible."[63] Therefore, this is more of a voluntary handshake in which space-faring nations can decide to implement (or not).

PART SIX

Protection Measures

Consistent with the guidelines established to mitigate the accumulation of more debris in space, protection measures exist to reduce the probability or consequence of a collision with space debris. These protection measures include shielding and collision avoidance maneuvers.

Shielding

Two shielding techniques used today include orientation and multi-layer systems. Shielding through orientation involves positioning the spacecraft to protect the most vulnerable or critical areas from debris. The Shuttle uses this technique whenever possible to protect the chambers occupied by the astronauts. Once in orbit, the payload bay positions towards the Earth, enabling the shuttle to be "safer by a factor of 20 relative to the worst possible orientation."[64] The second technique (multi-layered system) has a similar effect as the armor employed on military vehicles to protect against enemy fire. This technique is "designed to break up an oncoming particle and absorb the resulting energy", however, is dependent on the mass and velocity of the debris.[65] Because of this dependency (and the varying sizes of debris in orbit), one shielding design cannot protect the spacecraft from all types of debris. For example, the ISS requires over 200 different types of shielding.[66] Another disadvantage to this technique is the creation of more debris when the shields break off the satellite. A telescope recently observed around 55 faint objects in GEO (around 30 cm wide and traveling up to 1 km/sec), believed to be "thin layers of satellites thermal blankets…used to shield satellites from…space debris."[67]

For most spacecraft, shielding only offers protection against debris up to 10 mm in diameter.[68] The ISS is the exception in that it has been designed to shield the critical components (i.e., where the astronauts are located) from debris up to 1 cm in diameter.[69] The reason for this limited protection is that shielding increases the mass of the spacecraft, which increases launch costs. Other than offering some limited protection, shielding has no other usefulness to the operational performance of the satellite. "The cost of increasing the protection for critical modules on the Space Station from 1 cm to 2 cm has been calculated to be on the order of $100M for launch costs alone, not including research and development and manufacturing costs."[70] Thus, any attempt to shield a spacecraft from debris larger than 2 cm is not worth the reward.

Collision Avoidance Maneuvers

To protect spacecraft from larger debris, operators employ collision avoidance maneuvers. This technique requires early warning of debris on a collision path with a spacecraft to allow time for the operators to move the vehicle to a safer orbit. "It's now standard practice that near-Earth satellites carry an allowance of fuel simply for taking evasive maneuvers during the craft's operational lifetime."[71] NASA has conducted several collision avoidance maneuvers over the past few years, for example with the Terra spacecraft. Normal operating procedures require the satellite's engine to fire three to five times per year to compensate for atmospheric drag. However, in 2005 the engines fired specifically to prevent the Terra spacecraft from colliding with a large piece of debris from a U.S. Scout G-1 upper stage launched in 1983.[72] This procedure was required again in 2007 to avoid collision with a large piece of debris from the Fengyun ASAT test earlier that year. "Because of advanced warning, NASA only had to fire Terra's engine for a relatively short 1.3 second burst to move the satellite out of harm's way [from the Fengyun debris]."[73] So far, it appears this protection measure has decreased the probability of collision with debris, but the cost to provide this protection can be seen in the limited amount of fuel onboard the spacecraft, which can reduce the satellite's operational life.

PART SEVEN

Reduction/Removal Capability

Currently, the most cost effective (although perhaps not the most efficient) way to remove debris in space is through natural decay due to atmospheric drag. "When debris hits a part of the atmosphere it loses velocity; this lowers its orbit and increases the probability of it encountering more atmospheric particles…slowly drawing the debris into the atmosphere where it burns up."[74] However, this method is only possible for spacecraft and debris in LEO where a thin layer of atmosphere still exists, and the timeframe for de-orbiting depends on the altitude. For debris located at less than 600 km, it can take several years before it reenters, however, it can take decades for objects at 800km and centuries for objects higher than 1000 km.[75] Thus, the speed of reentry is directly related to the altitude of the orbit. Figure 2 shows the number of tracked objects (about the size of a basketball or larger) that de-orbited back to Earth between the years 1957 and 2007.[76] As shown, around 100 to 200 large objects (the size of a basketball or larger) reenter the Earth each year due to atmospheric drag.[77]

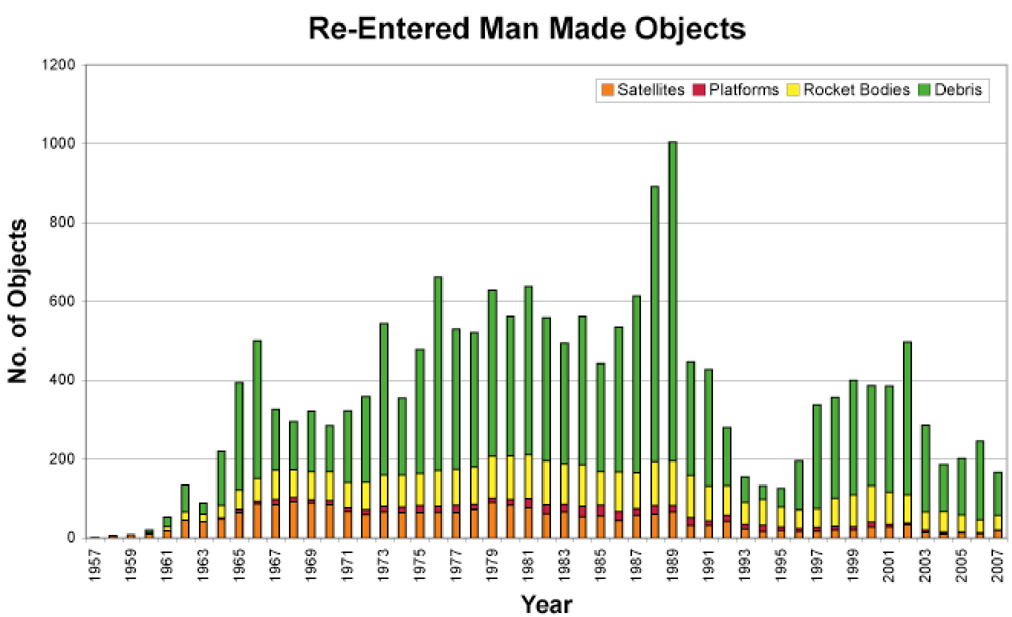

Figure 2: Annual Reentry Data from 1957 to 2007[78]

"On average, one non-functional spacecraft, launch vehicle orbital stage, or other piece of catalogued debris has fallen back to Earth every day for more than 40 years."[79] In most cases, this debris burns up entirely during reentry or lands in unpopulated (or sparsely populated) areas (i.e., oceans, Siberia, Canada, Australian Outback). For example, in July 2008 the owner of a three-million acre pastoral property in Australia found a solid rocket motor casing that landed 18 years prior from a U.S. Delta 2 launch vehicle.[80] Despite the regular occurrence of large debris falling back to Earth each year, "hazard to people or property from reentering space hardware is very limited…no known reports of death from such events have ever been received."[81]

Graveyard Boosts to Higher Orbits

For spacecraft located at an altitude too high for natural decay and de-orbiting to occur within 25 years, the best way to remove them from the protected regions of LEO and GEO is to boost them to higher orbits (typically 300 km above GEO). For this procedure to be effective, it requires the voluntary participation of satellite operators, who could maintain the satellite's position in orbit for three more months for the fuel required to boost it to 300 km out of GEO.[82] However, it appears to be an effective means for removing spacecraft from these protected orbits, largely because of the stake to keep these areas hospitable for future space operations. Even the commercial industry is implementing this procedure. In 2007, "of the 12 satellites that reached the end of their operational life, 11 were moved to a graveyard orbit 300 km beyond GEO, although one was re-orbited too close to GEO…compares to 2006 when nine satellites were correctly reorbited, seven were reorbited too close and three were abandoned."[83] Although graveyard boosts is a viable option for removing nonoperational satellites and spacecraft at the completion of their mission, it obviously does not apply to the spacecraft fragments and components that remain in orbit. Furthermore, it essentially kicks the can down the road in that it removes these spacecraft from the protected orbits but not from the space environment.

Electrodynamic Tether Systems

For spacecraft weighing more than 1000kg, an electrodynamic tether is a potential solution to assist with the removal of spacecraft in LEO at mission completion. This tether system consists of a conducting tether, a deployer, and the necessary control system and electronics to control the tether during deployment and operation. Essentially, the tether is a "long, flexible conductive cable…that moves through the magnetic field of the Earth."[84] While the satellite is operational, the tether is stored in the deployer and in sleep mode, performing periodic state of health checks on the satellite until either receiving the activation command to de-orbit the spacecraft or finding the satellite no longer operational after a state of health check. When activated, the conducting tether deploys and acts as an anchor to slow the satellite down by increasing the electromagnetic drag created by the Earth's magnetic field, thus speeding up the de-orbiting process. "Because the tether system can utilize the currents and voltages generated by the tether to power itself, it is not reliant upon power from the host spacecraft."[85] If this capability proves technically feasible, spacecraft located between 775 and 950 km altitudes could de-orbit back to Earth in 11 to 18 days (as opposed to centuries), and 37 days if located at 1390 km (as opposed to 9,000 years).[86] Industry is hoping to develop this system for less than $500,000.[87] Estimates also show that this tether system will likely consist of one to two percent of the spacecraft's mass (typically around 1000 to 2000 kg).[88] When considering that it typically costs around $12,000 per kilogram of payload launched to LEO, it would likely add $120,000 to $480,000 to launch a spacecraft that includes this tether system capability.[89] Thus, the estimated total cost to develop and launch this capability is less than one million dollars (per spacecraft).

Currently, Defense Advanced Research Projects Agency (DARPA) is funding a technology demonstration study to assess the feasibility of developing this capability. Although this may be a cost effective option for removing debris from LEO, it has yet to prove technically feasible. A 2006 IADC report concluded that, while ‘electrodynamic tethers have strong potential to become effective mitigation measures…various problems are still to be solved before this technique can be practically adopted.”[90] One of the challenges is the assurance that this system will not create more space debris (either from the tether system breaking off the satellite or the collision with other debris and space assets while de-orbiting).

Tape Module

For spacecraft weighing less than 1000 kg and orbiting at less than 850 km altitudes, a tape module is a potential solution to assist with the removal of spacecraft in LEO at mission completion. “The module is a pizza-box shaped unit, 30 cm x 30 cm x 2.5 cm.”[91] Similar to the electrodynamic tether system, this module is attached to the spacecraft before it’s launched and remains in sleep mode until activated, at which time it deploys a conducting tape several-hundred meters out from the satellite. Once deployed, it creates aerodynamic and electrodynamic drag through interactions with the Earth’s magnetic field. Industry is hoping to develop this system for less than $100,000.[92] Estimates also show that the mass of this module system is less than 3 kg.[93] Using the same methodology to estimate launch costs for the tether system, it would likely add $36,000 to launch a spacecraft that includes this tape module capability. Thus, the estimated total cost to develop and launch this capability is around $136,000 (per spacecraft). Same technical challenges apply as discussed with the tether system.

Grapple, Retrieve, and Secure Payload (GRASP) Technology

The tether and tape module solutions only apply to spacecraft, not the debris that's left behind due to fragmentation and breakup. The Grapple, Retrieve, and Secure Payload (GRASP) Technology is a potential solution to capture non-operational spacecraft (and debris fragmentation) in orbit. This technology uses "lightweight inflatable booms to deploy a large net structure, which can be maneuvered around a space debris object and then collapsed to securely capture the object." [94] After capture, a de-orbit system such as a tether or tape module described previously could be used to dispose of the debris. Very little else is known about this capability in terms of anticipated development costs or its mass (thus, estimated launch costs could not be determined). However, DARPA has funded a study to determine if this solution is technically feasible. Results were positive in that a prototype successfully demonstrated this capability. However, DARPA has not provided any additional funding to further the project.

Laser Space Propulsion

Another possible solution for the removal of existing debris and fragmentation is through the laser space propulsion. An Orion study conducted by NASA and the USAF in 1996 concluded that it was technically feasible to develop a capability to remove debris in space using ground-based lasers. The team took into consideration the different materials in which space debris consists of (aluminum, carbon phenolic, sodium/potassium metal, steel, and multiplayer insulation) and proposed a technique that uses the surface material of the debris as a propellant to either send the debris to higher orbits or de-orbit back to Earth. "In essence, the intensity of the laser must be sufficiently great to cause the material on the surface of the object to form a vapor, which as this hot vapor expands imparts a force or thrust to the object." [95] The optimal intensity of the laser energy depends on the material of the debris and the laser pulses' duration to create this propulsion. “This system would be effective against both metallic and nonmetallic targets in space, and could be effective against materials that are in higher orbital altitudes.”[96] Although technically feasible, another study conducted in 2000 assessed whether it was cost effective. This study used the Iridium satellite system and the number of objects in LEO as a basis for their estimate. The $3.450 billion system is comprised of 66 satellites (each satellite being worth approximately $50 million), and the estimated amount of damage to satellites in this orbit was found to be $40M per year.[97] The study concluded that one ground-based laser facility operating near the equator “could remove all orbital debris up to an altitude of 800 km in two years” for about $100 to 200M.[98] The team also recommended a technical demonstration study to further this concept, but it is unknown at this time as to whether anything is underway to make this capability a reality. However, one of the challenges facing the employment of this solution would likely be the ground facility’s dependency with the tracking capabilities existing today. It would seem that for this ground-based laser facility to be effective, it would require dedicated and improved tracking capabilities to track debris smaller than 10-cm, which again, can still damage a satellite and create more debris). Thus, the costs associated with this solution may not truly include a system level approach to employment.

PART EIGHT

Recommendation/Solution

Despite the increasing amount of space debris in LEO and GEO regions, and the limited accountability for damage and enforcement of debris mitigation practices, the risk of debris colliding with spacecraft does not outweigh the costs to develop capabilities to remove debris from orbit. Only one data point could be found relating cost impacts to space assets due to collisions with debris (estimated at $40 million per year), which is not conclusive enough to argue in favor of developing solutions to remove this debris. Perhaps this lack of data is due to the space community's fear of losing funding for more projects (if the risk is determined too high to conduct operations safely), or nation-states not willing to disclose incidents resulting in decreased space capabilities and increased vulnerabilities. Perhaps it is the employment of effective shielding and collision avoidance of mitigation measures. Whatever the reason, until a massive collision occurs that is large enough to make national news and get taxpayer's attention; it does not make sense expend dollars to develop capabilities to remove debris at this time. We need to be more proactive in fixing the near-term problem by instilling the discipline among space-faring nations to control the accumulation of debris before we can look to a long-term, debris-removing solution when searching for ways to protect the space environment in the future. Thus, the near-term solution for proactively protecting the space environment is to:

- Update Treaties and Space Law to contain legal definition of space debris, include all space-faring nation-state and non-state actors, and the mitigation measures established by the IADC. Also needs to prohibit the use of conventional weapons (i.e., ASAT weapons) from destroying spacecraft or satellites and include enforcement mechanisms to protect the space environment today and tomorrow.

- Improve existing detection and tracking capabilities (especially for debris 1 to 10 cm in diameter) to enable collision avoidance maneuvers to be possible. Additionally, establish an international tracking system, funded among all space-faring nations, to exchange tracking information and share the burden of developing this capability.
- Continue to conduct risk reduction technology demonstration studies to refine the capabilities discussed in this paper for safely removing debris from LEO in the event that nation-states continue to abuse the space environment.

If risk of collision increases (signifying need for removal mechanisms) and technical challenges for the potential solutions discussed are resolved (increasing confidence in cost estimates for development and employment) then a long-term solution would be a combination of tether/tape systems and ground-based lasers. Tether/tape systems would ensure spacecraft are de-orbited quickly upon mission completion to avoid the accumulation of non-operational satellites in LEO. The removal of existing satellite fragmentation and other pieces of debris would occur with the employment of ground-based laser to propel them out of LEO. However, no removal capabilities appear possible for removing debris in GEO (other than graveyard boosts), so there needs to be some focus on this portion of the problem to keep that orbit hospitable for future space operations. Unfortunately, there is no recommendation for this part of the problem.

PART NINE

<u>Conclusion</u>

It is clear that the amount of space debris is increasing in the protected regions of LEO and GEO. The number of launches per year continues to increase as well as the number of nation-state actors and non-state actors interested in exploiting the space domain. "Civilian programs are expected to represent two-thirds of the 616 government satellites to be launched from 2007 to 2016; the remainder will be military satellites."[99] Furthermore, the activities that create debris are outpacing the removal rate caused from atmospheric drag and graveyard boosts. This trend has led to a "net growth in the debris population in LEO at an average rate of approximately 5 percent per year."[100] As congestion continues in LEO and GEO, further debris is likely to generate as result of the satellite's close proximity to others and the rate of satellite breakups.

Given the increasing debris, it would seem the risk of collision would be high. However, the risk is only moderate in terms of probability and consequence of a collision due to the varying sizes of debris and protection measures currently employed. While debris that is l0-cm or larger can seriously damage or knock out a satellite, this debris is reliably tracked to enable more time for collision avoidance procedures to be accomplished. For debris less than one centimeter in size, the probability of collision is high but the consequence is low (partially due the size of the debris and the existing shielding measurers of the satellite's critical components). Although debris between 1 and 10 cm in size is too small to be tracked (but large enough to cause some mission degradation or loss), there is not enough information to argue the cost of damage due to collision outweighs the cost of developing solutions to remove debris from orbit.

Thus, the risk of debris colliding with spacecraft (manned and unmanned) is moderate and does not necessitate the development of this capability at this time.

However, there is a need to take active measures for protecting the space environment from the accumulation of more debris. These measures include achieving consensus from the international community on the legal definition of space debris and inclusion of this term in the existing Treaties and Space Law as well as prohibiting the use of conventional weapons (i.e., ASAT weapons) from destroying spacecraft or satellites. Furthermore, we need to improve the detection and tracking capabilities to reliably track and catalogue debris 1 to 10 cm in diameter, and establish an international tracking system in which all space-faring nations to share the financial burden of developing and operating. Finally, we should continue to conduct risk reduction technology demonstration studies to refine the tether, tape module, GRASP, and laser-ground propulsion capabilities discussed in this paper for the possible employment of future debris-removing solutions in LEO and look for ways to do the same for debris in GEO. Until a massive collision occurs that is large enough to make national news and get taxpayer's attention; it does not make sense expend dollars to develop capabilities to remove debris at this time. We need to be more proactive in fixing the near-term problem instilling the discipline among space-faring nations to control the accumulation of debris before we can look to a long-term, debris-removing solution when searching for ways to protect the space environment in the future.

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