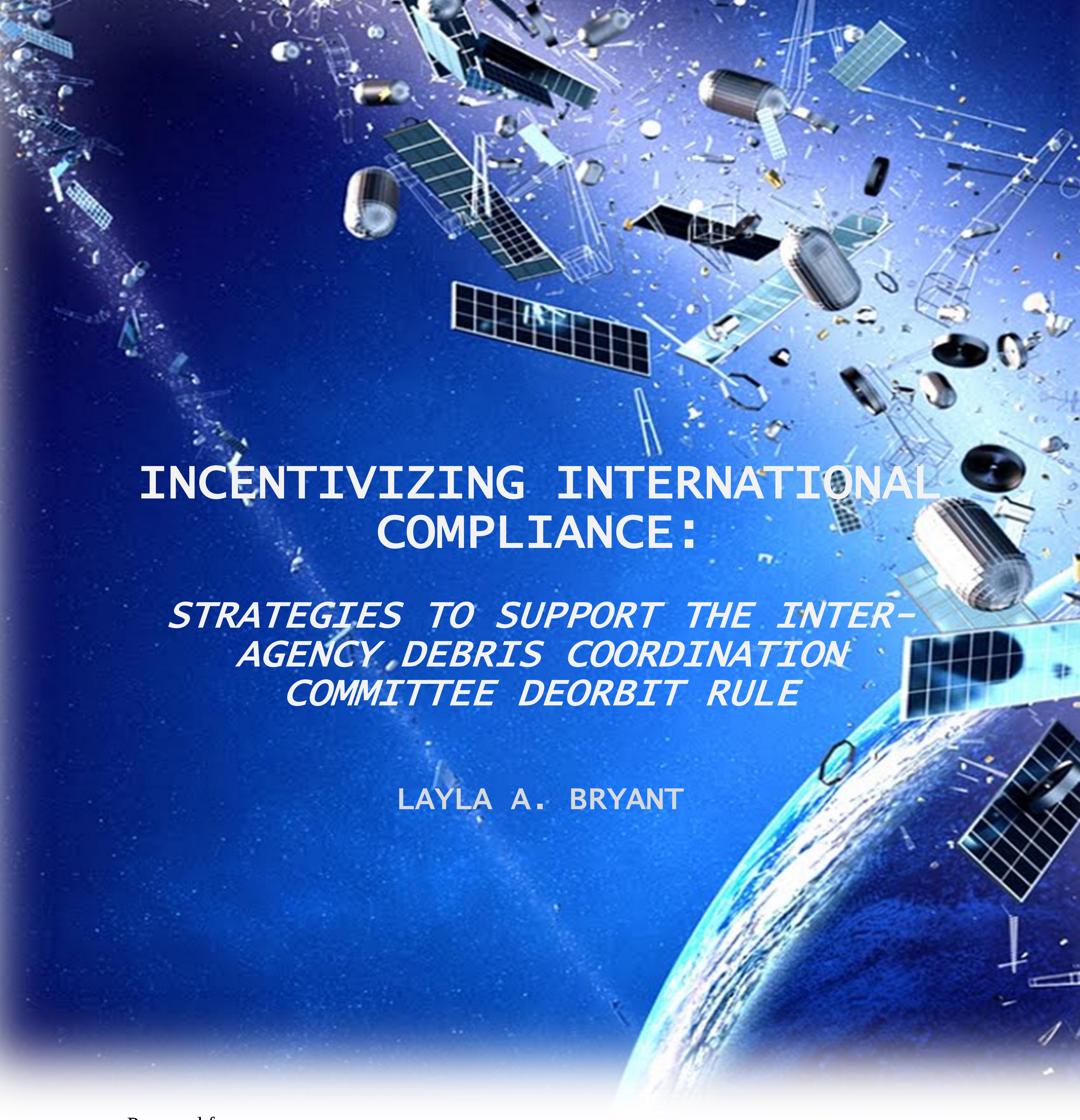

INCENTIVIZING INTERNATIONAL COMPLIANCE:

STRATEGIES TO SUPPORT THE INTER-AGENCY DEBRIS COORDINATION COMMITTEE DEORBIT RULE

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(Picture: Shutterstock, 2018)

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Disclaimer

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Definitions

This issue is highly intertwined with the mechanics of space flight and the abbreviations and terminology attempt to give all readers a general understanding of operations in space while focusing on the components of international cooperation.

Technical Terms

Collision: The intersection of two satellites in orbit, resulting in their destruction. There has only been one confirmed satellite Collison, though the risk of collision is increasing.
CubeSats: are built in (Units or "U") of 10 cm x 10 cm x 10 cm and typically weigh less than 1.33 kg (3 lbs. per Unit.) a subsection of small satellites (weighing under 500 kg)
Fragmentation: the unattributed breakup of satellite components from a collision, malfunction, or intentional destruction on-orbit.
Geosynchronous/geostationary (GEO): satellites circle the equator at 22,236 miles altitude.
Large Constellation: A network of satellites typically used for communications or imaging. Large refers to constellations containing over 100 satellites but can be upwards of 1,000
Lifetime: The amount of time a satellite spends operating on-orbit. A satellite or spacecraft becomes debris when it is no longer performing it's intended function also known as end-of-life.
Low Earth orbit (LEO): satellites operate from about 250 miles to 1,000 miles altitude.
Medium Earth Orbit (MEO): is generally considered to range from about 1,000 miles to 20,000 miles altitude.
On-Orbit: Refers to satellites that are in orbit and is the common term used due to the process of maintaining speed and altitude. On-orbit is frequently used to reference experiments and activities that occur during orbit.
Post Mission Disposal (PMD): The intentional change to an orbit after the end of functional operations using remaining fuel to boost or lower the orbit of a satellite to a predetermined location.
Rocket body (RB): space object designed to perform launch related functionality; This includes the various orbital stages of launch vehicles, but not payloads which release smaller payloads themselves. (ESA, 2019)

Acronyms

CONFERS – Consortium for Execution of Rendezvous and Servicing Operations
COPUOS – Committee on the Peaceful Uses of Outer Space
CSpOC – Combined Space Operations Center (formerly the Joint Space Operations Center)
DARPA – Defense Advanced Research Agency
ESA – European Space Agency
IADC – Inter-Agency Debris Coordination Committee
ISS – International Space Station
NASA – National Aeronautical and Space Administration
OST – The Outer Space Treaty of 1967/ Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies
SSA – Space Situational Awareness
SSN – space surveillance network
UN – United Nations

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Executive Summary

The most substantial collision threat to operating satellites is excess debris. Preventing the addition of defunct satellites to current debris is vital for creating a sustainable orbital environment. Satellites provide the infrastructure for GPS, weather, and communications technologies we have become accustomed to today. The addition of small satellites and large constellations is set to increase the number of satellites from 2,000 to over 20,000 in the coming years, adding to strains on the orbital environment (Lewis, H. Radtke, J., Rossi, A., Beck, J., Oswald, M., Anderson, P., Bastida Virgili, B., And Krag, H. (2017).). **With the rise of small non-maneuverable CubeSats and large satellite constellations in low earth orbit (LEO), stronger adherence to deorbit rules are needed to maintain operability.**

The guidance from the Inter-Agency Debris Coordination Committee (IADC) to deorbit satellites within 25-years of end of life was designed to prevent the accumulation of defunct objects in-orbit. The nature of governing a global resource in space where ownership of orbits does not exist makes enforcement of the 25-year rule infeasible. Despite enforcement struggles, research indicates that increasing compliance with the existing rule - which has a 60% compliance rate - can prevent an increase in collision risk as the launch rate increases (Sorge, 2017).

This analysis considers five incentive mechanisms for increasing current compliance with deorbit standards in LEO:

1. Individual Country Regulation (Current Method)
2. Differentiating Deorbit Rules for Different Types of Satellites
3. Forming a Deorbit Year Trading Scheme
4. Creating an Industry Consortium
5. Rewarding Responsible Behavior through Insurance

The options are evaluated on **compliance & verifiability, adaptability, cost, and implementation feasibility.**

To maintain a stable space environment, stronger international incentives need to exist for removal of satellites as they finish their functional operations**. I recommend Option 4, creating an international industry-government consortium to support adherence to a given deorbit rule.**

This strategy is flexible to accommodate changes to the orbital environment, uses a grassroots approach to develop consensus-based standards, and creates an accountability system that will bolster enforcement. The options could also be explored being implemented together in the future if there was an international entity willing to take on the cost.

Background

Problem Statement

The commercialization of space has led to both innovations and an increasing reliance on space assets. Today, the economic value of the space industry is estimated to be $348 billion (USD) and projected to be over a trillion by 2040 (U.S. Department of Commerce, 2017). Weather, climate and land environmental modeling, telecommunications, satellite internet, Global Positioning System (GPS), and more are dependent on satellite technology. The increased demand for such capabilities has resulted in congested orbits. Future economic opportunities are driving projections of 4,000-20,000 additional satellites in the next ten years (Foust, 2019). Small non-maneuverable satellites compound this problem because they may spend extended periods as useless debris (Pang, Bo, Meng, Yu, Guo, Zhou, 2016).

The past 60 years of space activity has resulted in over 8,000 satellites being launched. Today with 4,994 still in orbit, though only 1,947 of those satellites are currently active (Union of Concerned Scientists). As the number of dead satellites increases, the probability of collision increases exponentially (Kessler, 1988). To prevent an accumulation of dead satellites and increase in collision risk from satellite debris, the Inter-Agency Debris Coordination Committee and the United Nations adopted guidance to deorbit satellites in low earth orbit (LEO) within 25-years of the end of their mission, as an international standard. Complying with a deorbit rule in LEO often requires operators to expend fuel otherwise used to keep the satellite operating longer. The key to a safer space environment is *compliance* to a lifetime rule more so than the actual lifetime of debris in space. That means the rule can be 5, 10, 15, or remain 25 years, but the key to maintaining the environment is strict adherence or compliance to the standard (Bastida Virgil, B. & Krag, H., 2007). **Current deorbit rule compliance rates of 60% in LEO are unsustainable for preventing the pollution of LEO requires addressing post-mission disposal compliance for operators with deorbit capability (ESA, 2018).**

Creating a Stable Space Environment: Rate, Timeline, & Removal

Orbital debris, also known as "space debris"[1]*, consists of human-made objects orbiting the Earth that are no longer functional spacecraft. Such debris includes nonfunctional spacecraft, abandoned launch vehicle stages, mission-related debris, and fragmentation debris. (Alver & Gleason, 2018). Orbital debris can affect the cost, reliability, integrity, and capability of new satellite systems (FCC). It is a risk to public services and utilities, and it has the potential to cause physical harm to both people and property.*

The degradation of LEO from debris would impact all sectors of space activity – civil, commercial, and national security. Kessler's Syndrome, which first proposed the idea that collisions in space will exponentially increase from the first collision due to the propagation of debris, theorizes that at some point orbits will become unusable due to high collision probability. In a Kessler level projection of a cascade effect, entire regions of orbits could become cluttered with debris, increasing operating hazards and even yielding orbits inoperable.

[1] Orbital Debris and Space Debris will be used interchangeably from this point forward.

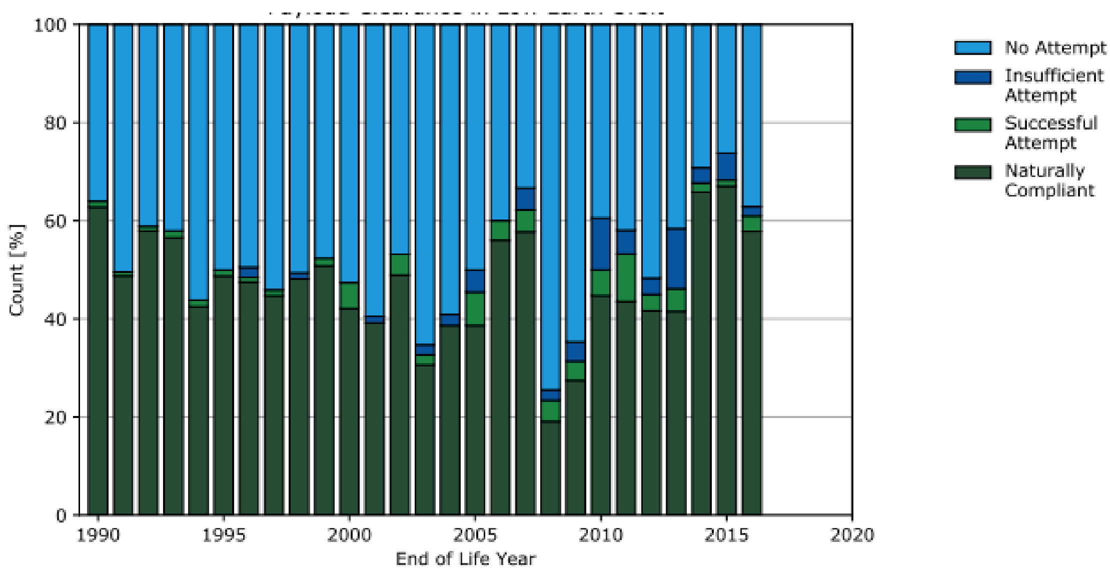
Active Debris Removal (ADR):
Removal of debris is currently a conceptual idea that many companies and engineers are looking at to stabilize orbits. There are many proposed systems of ADR through nets, orbiters, satellite servicing to extend life, and recycling components to build new satellites. The limitation of active debris removal is that there is no cost to satellite operators for non-compliance and therefore no short-term cost to operators and launchers for not removing or deorbiting satellites within 25-year. If there are no further launches, it would still take over 300 years for debris in LEO to deorbit, making ADR a necessary component of future sustainability (Bastida Virgil & Krag, 2009). To address some of the legal issues regarding active removal methods, industry and government have come together to get ahead of future regulation and to work towards making the remediation of debris a possibility. The Consortium for Execution of Rendezvous and Servicing Operations (CONFERS) is an international industry group that meets quarterly to work on technical challenges of active removal. The CONFERS program offers a model of how the industry can come together to develop a multi-stakeholder process. CONFERS' initial funding came from the Defense Advanced Research Projects Agency (DARPA), but the goal is for the program to become industry-funded within five years. Since Active Removal is both costly and there is currently no actor performing removal, other ways to achieve compliance need to be explored in the meantime.

The systems reliant on these satellites would also be at risk. Therefore, the large parts of the world economy is at risk from space debris. Particularly, telecommunications and weather forecasting which are two of the primary industries utilizing LEO and are expected to increase their reliance on satellite operations with the addition of 5G and internet services (Besha & MacDonald, 2016).

<u>There are three major components of creating a stable space environment: the rate of compliance with a deorbiting rule, the timeline of the rule, and the amount of active debris removal.</u> Technological advancements are part of the solution to mitigating orbital debris, but they cannot be successful without consequences for noncompliance with the deorbit rule (Sims, E., & Braun, B., 2017). High adherence with any year goal would reduce the amount of active debris removal they are needed to reach what the authors describe as a stable space environment (Frey, S., & Lemmens, S.,2017).

Deorbit guidelines exist to remove inactive space systems from the environment, lowering the risk of t collisions. Objects either deorbit naturally when they reach the threshold where Earth’s atmosphere creates enough drag for reentry or expend fuel to accelerate deorbiting. (See Appendix 1 for a discussion of difficulties predicting and planning natural deorbit timelines.) A third option is a movement to a graveyard orbit, but that is only viable for satellites in Geostationary Orbit (GEO). Since communication time is shorter with satellites in LEO, there are many more satellites than in GEO. There is also a predicted increase of space traffic within LEO soon for broadband internet and 5G.

Figure 1: Post Mission Disposal of LEO Payloads at End of Life Year for 2017



(a) Relative clearance of LEO_{IADC} by payloads.

Source: ESA, 2018

The European Space Agency estimates that "between 30 and 60% of all payload mass recently reaching end-of-life in the LEO over the past 20 years". As seen in Figure 1, the majority of LEO disposals are naturally compliant, but only a small number are opting to use controlled reentry (the light green section) to comply with IADC guidance. Compliance in GEO is over 90% while in LEO compliance has recently been about 60% (ESA, 2018). Only 12% of satellites with orbit control capacity are deorbiting upon the end of life (Morand et al. 2014). Compared to the GEO rule for movement to a disposal orbit, the amount of fuel to deorbit is about ten times more in LEO. (Macauley, 2015). The more costly fuel requirements and reentry risk in LEO make it more likely that an operator chooses to abandon a satellite in orbit (Schaub, Jasper, Anderson, & McKnight, 2015). The more time on-orbit after the end of life presents more opportunities to collide, regardless of the altitude (Brown, Cottom, Gleason, Hallex, Long, Rivera, Finkleman Hitchens, Jah, Sedwick, 2016).

Avoiding Collisions that Create Debris

In 2017, the United States Air Force Combined Space Operations Center (CSpOC) issued 655 notices to satellite operators warning of the likelihood for a satellite collision with a probability of .1% or higher. Of those emergencies, 579 were in LEO where space is relatively crowded, and a range of essential assets such as communications satellites, Earth observation satellites, and even the ISS reside (Horstman et al., 2018). Congestion in LEO is projected to more than double the population of active satellites for telecommunications networks. (J.-C. Liou, M. Matney, A. Vavrin, A. Manis,. Gates, 2018)

Satellites in LEO orbit at average speeds of 4 to 5 miles per second (7 to 8 km/s), or about 25 times faster than a jetliner (Mosher, 2018). In support of global space situational awareness (SSA). The United States military tracks and warns operators of collision probabilities. The JSpOC maintains the Space Surveillance Network (SSN) which is an attempt at a complete catalog of both active space objects and debris, but the system is only capable of tracking objects larger than 2 inches (5 cm) in LEO (Baird, 2013). The SSN helps to avoid a collision and attempts to limit risk through tracking individual objects and identifying close approaches. Collision estimation and debris monitoring systems are not perfect, and there is a broad range of uncertainty in collision projections (JSpOC). Removing satellites before they become defunct is vital because the space monitoring system has over a ½ mile margin of error at predicting collisions.

Iridium 33-Cosmos 2251 Collision: In February of 2009, despite a low probability of collision, a defunct Russian satellite collided with an active US satellite in LEO. Their likelihood of collision was below the notification threshold, estimated to miss by 584 meters (CelesTrack, 2009). The result of the crash of an inactive satellite was the destruction of both satellites, 2,000 pieces of trackable debris and many more untraceable. The wreckage was scattered over 1,700 meters throughout space, threatening every operational satellite in LEO (Secure World Foundation, 2010). The Iridium-Cosmos collision is the first known collision of an active and inactive satellite. Following the collision, fault was not established under the UN liability convention. Following the crash, the U.S. began performing conjunction assessment and issuing Space Situational Awareness sharing with other nations.

Even small objects and seemingly minor collisions can yield high risk and damage within the space environment. The International Space (ISS) executes collision avoidance maneuvers at least once a year. Performing a collision avoidance maneuver is disruptive to the mission and expends fuel, shortening the lifetime of a spacecraft. The ISS is periodically refueled to extend mission life and boost its orbit, but not all spacecraft readily have that capability. Preventing the accumulation of further debris is vital not just to the sustainability of orbits but also for the safety of human spaceflight and exploration. In April of 2016, a piece of debris hit the ISS and cracked the window.

How the 25-Year Rule Prevents Creation of Orbital Debris

The most substantial collision threat to operating satellites is from debris. Preventing the addition of defunct satellites to current debris is vital for creating a sustainable orbital environment. It is projected it would take over 300 years for debris currently in LEO to return to earth (Bastida Virgil & Krag, 2009). As the orbit of objects decay due to Earth's gravity, they typically burn up in the atmosphere. As shown in Figure 2, there is a massive debris cloud surrounding the earth. [2] While there are other crowded orbits, LEO suffers from the most congestion because of it more accessible, has the most satellites, and is used for significant telecommunications networks.

[2] Visualization of space debris with a diameter > 1cm scaled to make debris visible at one pixel.

Figure 2: Visualization of the Space Debris Environment in 2018

Source: Horstman, et al., 2018

While other forms of debris outnumber spacecraft debris, spacecraft have the highest mass and cross-sectional area, putting them at high risk of collision. Satellites also create the most debris in the event of a collision (IADC). Satellite breakups contribute to debris in three main ways: through fragmentation, accidental collision with other objects (debris, satellites, meteors), or intentional destruction (Anti-satellite weapon test). Limiting the amount of time on-orbit after the end of life operations reduces the chance of accidental fragmentation or collision (Liou, Matney, M., Vavrin, A., Manis, A., & Gates, D., 2018).

International Guidelines to Limit Satellite Lifetime

The United Nations Committee on the Peaceful Uses of Outer Space runs the Inter-Agency Space Debris Coordination Committee (IADC, 2002). Global cooperation through the IADC thus far has created guidance for deorbit at 25 years after the end of satellite operations. Space-faring nations are left to define how they follow or enforce the 25-year deorbit guideline. This guideline has the potential to create a scenario in which space actors prioritize individual short-term gains over long-term collision prevention even though it is in the best interest of everyone to preserve the usability of orbits. As the number of dead satellites increases, break up and potential collision risks the creation of more debris, threatening the long-term access to space assets.

The *Orbital Debris Mitigation Standard Practices* is based on NASA guidelines developed in 1990. Various countries and organizations, including Japan, France, Russia, and the European Space Agency (ESA), have followed suit with their own corresponding orbital debris mitigation best practices. Many of these countries tie their deorbiting to their launch and operating licensing regimes, but it is not required. While the IADC evaluates and creates guidelines, none of the international organizations or any individual government can adequately regulate compliance. Predictions of this rule is almost impossible given uncertainties in deorbit timelines from solar cycles and atmospheric expansion along with no international enforcement entity to monitor whether operators are able to meet deorbit rules (Nehrenz, M, 2012; Sagieres L, & Sharf, I,2017; Marcos, F., B. R. Bowman, and R. E. Sheehan, 2006). Figure 3 summarizes the roles of different international organizations in mitigating debris.

Figure 3: Table of International Guidelines on Debris

Abbreviation	Name	Document/Guidance
IADC	Inter-Agency Space Debris Coordination Committee	Developed IADC Space Debris Mitigation Guidelines (2002)
ISO	International Organization for Standardization	ISO 24113: on Space debris mitigation requirements (2011)
COPUOS	UN Committee on Peaceful Uses of Outer Space	International Space Agencies Convention on International Liability for Damage Caused by Space Objects (1973)

Adapted from Gleason & Alver, 2018

United Nations Committee on the Peaceful Uses of Outer Space

A limitation of IADC deorbiting guidelines is the fact that they are voluntary. Previous COPUOS treaties have had little consequences for failing to meet the conditions and offers easy withdrawal (Doleman, 2002). Increased commercialization of LEO has also led to questions of signatory country's oversight responsibility to private entity actors.

In the case of a collision, Articles II and III of the Convention on International Liability for Damage Caused by Space Objects (1973) defines an international legal regime to mitigate liability and strengthen international cooperation. According to the Convention, the claims commission was established to assess the damage and determine compensation for damages caused in a launch, orbit, and reentry (UN, 1973). The Liability Convention has never been used to settle an instance of satellite collisions (Weeden, 2010).

International Organization for Standards

The International Organization for Standards sets technical operating standards for a broad range of globally interoperable systems. "ISO 24113 aims to ensure that spacecraft and launch vehicle orbital stages (the engine sections used to propel the spacecraft that are discarded after use) are designed, operated and disposed of in a way that prevents them from generating debris throughout their orbital lifetime" (ISO, 2011). The ISO attempted to codify the IADC guidelines, but since there is not a current capacity to verify compliance, the ISO standard violates the fundamental principles and rules of standardization, that requirements be measurable and verifiable (Finkleman, 2015).

Anticipated Issues with Future Sustainability

Governments are concerned with a range of technological developments leading to more satellites. “The current period of innovation in the space industry has resulted and will likely continue to result in a significant increase in the number of satellites and types of operations in orbit, both of which have the potential to increase the amount of orbital debris. Thus, mitigating the growth of orbital debris is more critical than ever to ensure continued, safe operations in space" (Federal Communications Commission, 2018). As radical innovations change the space market and increase the total number of satellites, they may also pose risks of creating debris.

CubeSats

The proliferation of CubeSats may require new mitigation rules, mainly because some might be too small to project collision risk accurately and they spend long periods on orbit after completing their missions (Finkelman, 2010). CubeSats are small satellites designated as research spacecraft and built to standard dimensions (NASA). Launches for CubeSats increased from 6 per year in 2003 to over 120 per year as of 2015 (Pang, Bo, Meng, Yu, Guo, Zhou, 2016). These CubeSats are frequently flown as secondary payloads on other missions, which keeps launch costs low. Their small size is a plus because they contain less material that could be transformed into spacecraft-threatening debris (Kessler,1981). The small size is also a threat due to their high numbers, limited reliability, and inability to maneuver to avoid a collision.

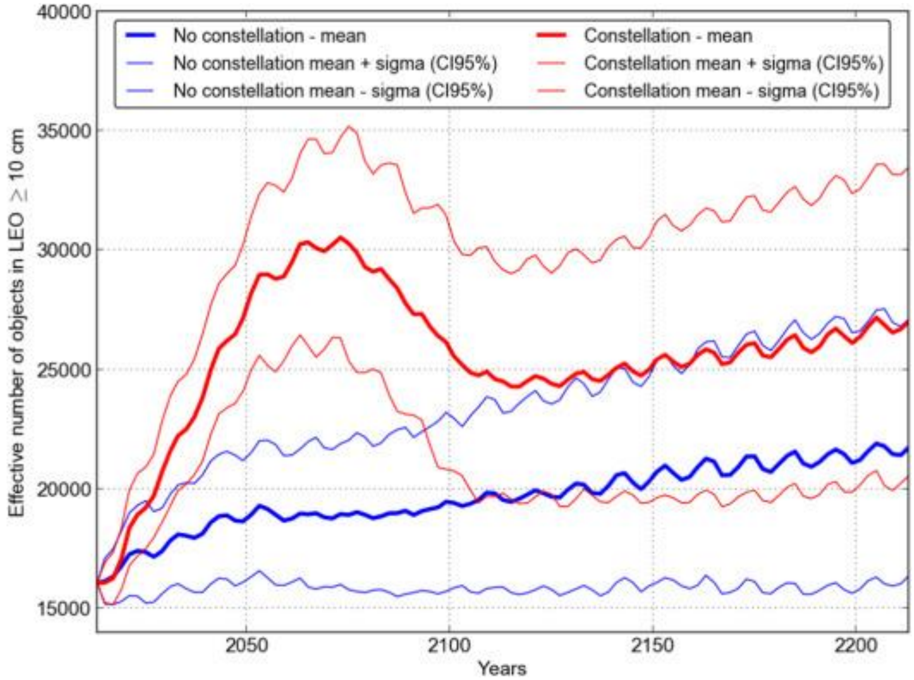
While most CubeSats are designed to end their orbital life within five years of launch, objects in orbits over 800 km take up to 150 years to re-enter earth's atmosphere (Peterson, et al., 2018). Researchers at NASA found that one of every five CubeSats launched between 2003 and 2014 violates international deorbiting guidelines (Pang, Bo, Meng, Yu, Guo, Zhou, 2016). Additionally, 25-years is a long time to remain on orbit when mission lifetimes are short, is an inefficient use of an orbit, and poses an unnecessary risk to other objects (Vedda, 2017). The future projection of more CubeSats and small satellites launched without a capability to deorbit holds the potential to decrease compliance with a deorbit rule.

Mega-Constellations

Another component of the future space environment is large constellations. Companies such as SpaceX, OneWeb, and Boeing are proposing constellations of over 1,000 satellites each (Cates, Houstan, Conley, Jones, 2018). Altogether, the industry has proposed adding about 20,000 satellites into non-geostationary orbits. These networks of satellites are sometimes referred to as mega-constellations. Their goal is to bring affordable broadband internet and other satellite services to areas throughout the world. These plans increase future launch demand as well as straining the sustainability of LEO.

NASA’s Orbital Debris Program Office’s *Large constellation study* also concluded that 99% of large constellation must adopt a shorter five-year rule “to prevent a dramatic increase in orbital debris” (2018). Further works analyzing the risk from constellations show that the increase in orbital population and collision risk could be mitigated through post-mission disposal compliance and reducing post-mission lifetime (Somma, Lewis, Colombo, 2018).

Figure 4: Comparison of the Long-Term Evolution of the Number of Objects in LEO with and Without Satellite Constellations.



Source: (Bastida Virgili et al., 2016)

Figure 4 shows that with the addition of one synthetic constellation comprising of 1,080 satellites, the predicted number of objects increases by over 10,000, even under the conditions of 90% successful implementation of post-mission disposal guidelines with 25 years orbital lifetime after disposal. Since the 90% compliance is much higher than average compliance in LEO of 60%, even this outlook is overly optimistic. Since there are currently many companies proposing and in various phases of producing these constellations, the impact of constellations on debris creation will be much larger than in Figure 4 which only consider one constellation. Finkelman estimates that only about half of operations have followed the existing guidelines, due to the lack of enforceable regulations (2017). These vast networks threaten an increase in debris and therefore collision risk. Additionally, the scale of these projects does not fit with the currently developed rules. If the 20,000 satellites for constellations posed by telecommunications companies are launched into orbit, compliance with the 25-year rule will not be enough to manage the long term sustainably of space (Lewis, H., et al., 2017).

Challenges for Enforcing Compliance

Difficulties with the enforcement of the deorbit rule is a component of a common property resource. Since orbits are a resource where it is not possible to prevent operators from reaching an orbit in LEO and where the use of an orbital slot prevents simultaneous consumption it can be considered global property or the "heritage of all mankind." The nature of being a common property resource (CPR) is congestion which is beginning to occur and destruction through a concentration of debris in an orbit preventing satellite operation. Overcoming the overuse of CPRs can be done through Elinor Ostrom's principles of "Sustainable Governance" for a global shared pool resource without top-down government regulation which is unfeasible at an international level for space. Ostrom presents empirical evidence that many CPRs can be successfully governed without resorting either to a centralized government or a system of private property.

> "As is true for many environmental problems, the control of the orbital debris environment may initially be expensive, but failure to control leads to disaster in the long-term. Catastrophic collisions between cataloged objects in low-Earth orbit are now an important environmental issue that will dominate the debris hazard to future spacecraft."
>
> - Donald Kessler

Ostrom's commons governance theories, in the context of space, point out failures in space governance, "[for] example, both COPUOS and the Conference on Disarmament have been used to create binding agreements and operate by consensus, but exclude private entities from being formal members, limit the role of non-governmental entities, and have strict limits on their mandate" (Weeden & Chow, 2012). While COPUOS and the IADC serve to recommend international norms, there is an opportunity to create a stronger global governing body for private actors in space. As a technology control, the 25-year rule is yielding a poor level of compliance for creating stable orbits because of the lack of enforcement and prioritization of short-term gains (Bradley & Wien, 2009). Similar to environmental economics, a technology control such as the 25- year post-mission disposal rule, is one of many ways to reach an acceptable amount of pollution. Other incentives to reduce pollution could be ceilings or taxes, subsidies for reduction, tradeable permits, and non-compliance fees. The incomplete governance of Outer Space provides both an opportunity for adaptive management that allows for rules to be flexible over time, as well as overcome challenges to enforcement, legitimacy, and agreement.

In space governance a centralized enforcement mechanism and private property are implausible to develop so relying on incentivizing the existing 25-year rule is key to improving compliance. Fundamental principles that could apply to the outer space regime include ensuring those affected can participate in the modernization of rules and developing systems that could be carried out by community members. These principles create buy-in at levels rather than relying on the weak enforcement mechanisms for space. The collective action problem is highlighted by the fact that there is no short-term cost to operators and launchers for not removing or deorbiting satellites within 25-years, but there are long-term costs to society and future users of the space environment.

When the Outer Space Treaty of 1967 (OST) was created, the only viable space actors were nation states. However, today there is a growing international commercial space industry, and the goals of the Treaty were not developed with commercial space companies in mind. Today countries oversee their aerospace industries' adherence to international agreements. Ownership in space based on the United Nations agreements is forever, yielding legal difficulties to debris removal techniques such as active removal since even debris is owned forever by the launching state.

National Space Actors

In the absence of internationally binding and enforceable laws that could control the creation of debris, some spacefaring nations have started to implement national laws (ESA). Since all spacefaring nations have a vested interest in keeping LEO as safe as possible and avoiding liability, they developed their own sets of guidelines. These rules have varying levels of detail and enforcement, but many share fundamental elements from *the NASA Government Orbital Debris Mitigation Standard Practices.* The UN Liability Convention drives the creation of national laws because it holds launching states liable for casualties and damage caused by the reentry of their space objects. The convention associates the liability to countries; the national laws make sure that the space operators in the respective state take precautions to mitigate risk (ESA, DISCOS).

The French Space Operations Act, which came into force in 2010, ensures that the technical risks associated with space activities are appropriately mitigated. The French Space Operations Act states that a satellite or launcher element placed on an orbit crossing the LEO protected region shall reenter the Earth atmosphere by performing a controlled re-entry, or, if impossibility to do so is duly proven, to reenter the atmosphere no later than 25 years after its end of mission date (UNOOSA, 2016).

Avoiding Strict Regulation:
Swarm Technologies, a Silicon Valley startup launched 4-picosatellites (Space Bees, ¼ the size of a CubeSat). The Federal Communications Commission denied swarm a license due to the small size of the satellites. Despite the denial, the satellites were launched on an Indian PSLV from India. Spaceflight, the company that set up the ride-share claims it did not know the satellites were unlicensed and has said they will do better in the future. The FCC regulates all satellite launches by American companies, regardless of where they occur, issued Swarm a $900,000 (USD) fine for transmitting to the U.S. (Foust, 2018). The question raised by this incident is who would be liable, the company's country or the launching country? India denied responsibility for the SpaceBees, and they were unlicensed by the US. This marks the first occasion that a private organization has launched a spacecraft without the approval of any government. With more commercial actors in space than ever, is there a risk of this becoming normalized? Alternatively, will strict regulation lead to "tax havens" for launch in countries?

In 2018, the United Kingdom passed the Space Industry Act. Section 38 of the act requires holders of launch licenses and others engaged in spaceflight activities to be insured (Houges, 2018). The requirement to hold insurance applies to all activities regulated within the act including spaceport operations, launch, and on-orbit. The UK is the first country to require on-orbit insurance for satellite operators. Insurance companies have a clear incentive to reduce risk since they would prefer not to make payouts. Reducing the number of inactive satellites reduced the amount of risk insurance companies must take on to insure operators. If more countries follow in the UK’s lead and require insurance for operators, there is likely to support from space insurance companies to find ways to incentivize a reduction in collision risk. It is a strong possibility given that the UN liability convention holds countries accountable and countries with more space assets may want to require their companies to carry insurance to divert some of the liability to operators. A factor for creating a stable space environment is the need for these international incentives to support compliance rules, especially given the unenforceable nature of space agreements. Compliance is also contingent on who is bearing the direct cost of deorbiting.

Company Level

The space industry is made up of satellite operators and manufacturers, launch providers, and data management services. Airbus Defense and Space (France), Boeing (U.S.), Thales Group (France), Lockheed Martin Corporation (U.S.), and Mitsubishi Electric Corporation (Japan) are some of the established market players.

Qualitative interview analysis from Walter Tam’s 2015 review of Space Debris and Satellite Manufacturing suggests that many United States Satellite companies are open to and desire an international governing body to develop and enforce end-of-mission requirements. Tam’s interviews with over 80 commercial satellite operators indicate that companies are willing to bear some burden of cost to maintain the space environment and they understand the costs of overuse. If every space company must pay these costs to launch a satellite, then they can be passed on to the end user. The problem arises when there is no enforcement, so no single company is willing to absorb the cost; they will not be able to pass it on if their competitors are not doing the same. Private companies must navigate specific country regulation and international guidelines, meanwhile, governments may find it challenging to cede power to an international governance system (Williamson, 2012).

> “A SIX-MONTH EXPERIMENTAL SATELLITE MAY SPEND 50 TIMES LONGER AS A NON-FUNCTIONING, HYPERVELOCITY PROJECTILE THAN THE AMOUNT OF TIME IT SERVED A USEFUL PURPOSE. FOR MANEUVERABLE SPACECRAFT, THE ADDITIONAL COST TO DEORBIT IN FIVE YEARS RATHER THAN 25 IS RELATIVELY MINOR, AND WE PROPOSE THIS AS A REASONABLE UPPER LIMIT.”
>
> – WALT EVERETT & DOUG ENGLEHARDT

Companies that have a long-term stake in maintaining a sustainable space environment for future business will vest higher stake in responsible space operations and push for others to do so as well. As Everett and Englehardt mention above, their companies, One Webb and Digital Globe want to see shorter timelines for deorbiting, both due to the risk from short term research CubeSats and because the cost to maneuverable spacecraft is low. Creation of global operating norms using the momentum stated by concerned operators may assist with future compliance. Global norms are "the shared expectations or standards of appropriate behavior accepted by states and intergovernmental organizations that can be applied to states, intergovernmental organizations, and/or nonstate actors of various kinds" (Khagram, Rikker, and Sikkink, 2002).

Overview of Strategies for Incentivizing Compliance

There are many different levels of intervention to incentivize international cooperation -- from country-level regulation, creating global markets, stakeholder collaboration, and financial incentives. The following are five incentive strategies for LEO:

1.) Individual Government Regulation

Individual country enforcement of UN agreements and deorbit rules is the status quo. This has allowed countries to create regulatory incentives for compliance. Currently, at least six countries have regulations for launch that require companies to attempt to meet the 25-year rule. The COPUOS guidelines can be promulgated into national laws, as with the French Space Operations Act. Nations could choose to lead by example and require more stringent guidelines, though they would risk outsourcing industry to countries with rules that are less strict.

2.) Differentiating deorbit rules for different types of satellites

Having different deorbit rules for different satellites can incentivize particular architectures and on-orbit behavior. This could lead to an increase in demand for specific types of satellites to increase demand for launch to specific orbits (such as below 600km) to ensure deorbiting compliance. This attempts to get ahead of impending changes from large constellations and non-maneuverable small research satellites. Similar to how LEO and GEO satellite disposal is not a one-size fit all policy, it would differentiate satellite types and require more tailored guidelines. The incentive for this rule is regulatory, and it could be implemented at several different levels, being international, country, or through industry consensus.

3.) Forming a Deorbit Year Trading Scheme

Similar to the carbon tax credit concept to battle climate change, this deorbit trading scheme creates an economic, market-based incentive for satellite owners and operators. Under this option, an agreed upon international entity would certify that a satellite met the deorbit requirement and operators could sell remaining on-orbit years to other satellites. This market mechanism reduces the cost of deorbiting for operators. This would require international cooperation to create a market place for trade and an organization for certification. The Kyoto Protocol and Paris Accords on Carbon Dioxide emissions offer ideas and lessons for the implementation of trading schemes.

4.) Creating an Industry Consortium

Industry consortiums work to set operating standards and allow groups to get ahead of and influence regulations. The value of a consortium for debris mitigation is industry-consensus buy-in and subsequent communal pressure. With sizeable initial participation, there will be a need for most operators to be involved. Including private entities can expand the role of non-governmental entities and add cooperative pressures to improve compliance (Weeden & Chow, 2012). A consortium allows for a bottom-up approach to creating industry-driven standards for best practices. The intent is for companies to have an active role in the process and thus increase the likelihood of compliance. A model for building a space industry consortium is CONFERS. It is actively trying to create industry consensus standards and norms of behavior for on-orbit satellite servicing.

5.) Satellite Insurance

Satellite insurance could offer monetary incentives to good stewards of the space environment. Similar too good driving or health, reducing the risk of collision helps both insurance providers and operators. Space insurance is the third highest program cost to satellite operations after satellite and launch services. If more satellites are insured, the cost of insurance may continue to lower and as collision risk increases it is likely that more satellites will seek insurance. Therefore, the future insurance market for space systems is expected to expand (Market Watch, 2018). Coverage for satellite operators and manufacturers, through the life of a satellite or payload, offers a unique opportunity to tie deorbit incentives to on-orbit or reentry insurance (AXA XL).

Metrics for Evaluation

The goal is to minimize the creation of debris and avoid increasing collision rates, no matter how long a satellite might remain in orbit. Incentivizing satellites to deorbit upon the end of their lifetime and to comply with any deorbit rule is the key to improving space sustainability given present technology. The evaluation criteria used to score the five incentive strategies are compliance and verifiability, adaptability, cost, and implementation feasibility.

Compliance & Verifiability

It is essential that actors not only comply but also that others can confirm compliance. A necessary component of international agreements and treaties is verification that the deal is being carried out. The current rate of compliance with the 25-year rule is around 60%. Ideally, a strategy will increase the number of satellites with deorbit capability that deorbit before 25-years (or whatever a future year limit may be). Using past examples as precedent, the change in compliance over five years will be projected for each strategy. This section will attempt to quantify how verification changes under different alternatives. The verification of deorbiting can increase accountability of actors in space, leading to the goal of more responsible space actors.

Measuring current compliance will be done using the Union of Concerned Scientists open source database of satellites and estimating the number of satellites that are capable of deorbiting, either through natural processes or through controlled reentry. The most successful strategies will increase both the percentage of satellites that are naturally complaint and the number of operators who perform controlled reentry.

Adaptability

To measure adaptability, strategies are evaluated on how responsive they could be to changes in the environment. Considering recent innovations, it is crucial that strategies are flexible to innovations. Rigid rules that require 20 years to reach consensus become outdated during rapid technological changes that are currently occurring in the space environment. Selecting an intervention that has the flexibility to create a sustainable impact on compliance will help solve some of the issues with the current 25-year guideline in LEO.

Adaptability is evaluated through the class of satellites whose incentive to deorbit will improve and how flexible the strategy is to future changes. For example, the current incentive of individual regulation allows countries to be flexible, but globally it does not allow for quick changes to the deorbit timeline based on the number or type of satellites being launched in the future.

Cost

The cost is considered in terms of international organizations, nations, and industry. There are substantial costs associated with creating too much bureaucracy and not increasing the functionality of the system, especially on a global level. Different strategies will have overhead costs and administrative costs that differ based on who is leveraging the incentive. Secondly, there is a direct cost of deorbiting the satellite through fuel and additionally, an opportunity cost of continuing profitable operations for up to a year longer if a spacecraft were not to perform a deorbit maneuver.

Implementation Feasibility

The feasibility criterion speaks to the implementation of any of these incentive structures. There are two components, political and administrative. Feasibility is qualitatively assessed based on the number of actors that must be brought together, precedent, and willingness to take on an implementation role.

Political

The level of international cooperation required and changes to current international rules should be evaluated to discern which options can make it through the hurdles of international consensus on not just a company level but also industry. Companies are beholden to the regulations of countries, but there is a balance between attracting space business and maintaining the space environment.

Administrative

Whether or not the incentive requires a complete overhaul of current mechanisms or improves the existing incentive structure. The setup and complexity of the option along with the enforcement or accountability mechanism that the strategy offers.

Evaluation of Incentive Mechanisms

The scope of the intervention: both in terms of the distribution of satellites from industry vs. government and the level the enforcement is carried out (self, community, international, country). The enforceability of the options is examined based on how strong the regulations/incentives are. Additionally, industry experts were consulted on compliance estimates and the evaluation of social incentives and pressures.

Methodology

The goal is to prevent aging satellites from becoming inactive debris through end-of-life deorbiting. Since there are difficulties in predicting the future space environment and quantifying the ramifications of a single collision, this paper uses a cost-effectiveness analysis and does not quantify the benefits of a safe operating environment. In the future, a quantification of the long-term benefits of space sustainability would be useful. The difficulties in performing this are the costs to secondary industries and both the modern world's economic and functional reliance on space systems. My analysis assumes that the level of increase in compliance is worth the money spent on this. Much of this assumption is because there are currently no other viable alternatives such as active debris removal or enforcement.

Effectiveness is estimated using how many current satellites can comply or would be encouraged to do so under different strategies. Compliance estimates rely on the existing space environment only because of uncertainties future satellites. A fundamental assumption is that satellites around the 600 km threshold will naturally deorbit and only those above 600 km with fuel are capable of deorbiting.[3]

Qualitative case examples are used to imply adaptability and implementation challenges, as well as inform compliance rates under specific alternatives where a basis is not possible. I did not consider using fragmentation rates or collision risk as an outcome since the number of satellites increases because those will increase as the number of total objects increases.
Appendix 2 outlines the present net cost over 5 years using a discount rate of with future values from 1% to 5.5% to look at the outcomes. The cost calculations assume 2018 dollars. Cost is estimated through case analyses of similar programs, using UN budgets, various government spending, and the cost of deorbiting.

Finally, are several difficulties with extrapolating today's cost, technology and activities to the distinct future given the rapid pace of innovation and change to the environment. This body of work attempts to be transparent in assumptions made and their sources are based on educated guesses and the literature available. Case studies have been used to supplement compliance effectiveness estimates to fill in the gaps between the strategies in the space environment. In an ideal evaluation, the cost of mitigation would be balanced with the operational risks. Since this evaluation focusing on reducing collision risk through compliance mechanism, the outcome chosen is the percent increase in compliance for every dollar spent.

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[3] In the future it may be possible to deorbit through other types of propulsion, proposed as drag parachutes and solar sails, they are not included though these technical improvements could also assist with increasing compliance rates.

Figure 5: Assessment of Strategies for Incentivizing Compliance

Fails to meet objectives

Meets some objectives but fails others

Meets all or nearly all objectives consistently

	Increase in Compliance Above Present Day	***Adaptability***	***Cost Above Status Quo***	***Implementation***
1.) Status Quo	0%	Impending constellations make current levels unsustainable	No additional spending	No change
2.) Differentiation	0%-% *	Short term addresses the rise of CubeSats & Constellations	Changing the rules would come from governments cost of meeting	Rewriting the guidelines do not change compliance, hard to gain consensus
3.) Trading	10%-30%	Balances ease of deorbiting with high cost/difficult to deorbit satellites	Overhead & Organization. Kyoto was costly	Difficult to get countries to opt into trading schemes
4.) Consortium	0%-15%	Industry chooses participation and standards. Able to adapt to the environment through collective action	Set up and maintenance, based on CONFERS	The industry acknowledges the need for change and future implications of more debris
5.) Insurance	0% -20%*	Constellations & CubeSats most likely to self-insure	Minimal net costs	Balances deorbiting with insurance interest of reducing risk

*Indicates a high level of uncertainty based on design and future environment

Discussion of Results

Status Quo

After the passing of the IADC *Space Debris Mitigation Guidelines* in 2010, there was a slight decrease in fragmentations for three years following adoption (Horstmann et al., 2018). Finding a way to sustain increases in compliance, as well as make the guidelines more flexible to innovation would help strengthen current compliance mechanisms. The French Space Operations Act of 2008 offers one example of a countries attempt to codify IADC, ISO, and UN standards into domestic law. No one else has agreed to enforce these guidelines.[4] Only time will

[4] The United States has internalized the NASA Space Debris Mitigation Guidelines that inspired the IADC guidance in the FAA licensing process which requires plans for deorbiting to be submitted. However, it is through the regulatory process and is not required by U.S. law.

tell if more countries will follow in France's lead or if companies in France will have difficulty competing in global markets. That is why this strategy received the lowest rating for effectiveness at improving compliance and verification of a deorbit rule.

The trend towards increased government enforcement through a top-down will not necessarily motivate satellite system operators and spacecraft manufacturers to consider long-term approaches to space debris regulatory compliance making it unsustainable.

The current cost of the alternative is the cost of deorbiting to compilers and the regulatory burden that each country opts into taking on. It is an acceptable level of spending because it is what is currently spent.

As the current standard, this option is feasible but does require industry to take on an execution role and costs. Manufacturers must closely monitor orbital debris regulatory and policy developments around the globe because changing requirements will directly affect how operators approach satellite procurements. Compliance with various national and international guidelines as the number of objects in LEO increases may result in higher system development and operations costs and may present increased technical complexity and risk failure.

Differentiated Deorbit Rules

Assuming rules would be altered to alleviate concerns regarding future constellations and CubeSats and that these would be effective, compared to the current regulatory scheme, it is expected to increase compliance of current satellites by about 5% based on the number of satellites that could currently deorbit and previous impacts of rule changes. This estimate does not include the potential of significant returns it could have for deorbiting future constellations since the number and rate of the launch is unknown at this time. This rule does not increase the transparency of deorbiting and compliance would still be under the discretion of individual countries.

In the short-term specific changes would leverage satellites that have orbit control capability since satellites without the capacity are stuck in the orbit they were launched into regardless of rule changes. In the longer term, it could increase the uses of certain types of satellites that are designed fo deorbited effectively. It could also increase the demand for different types of deorbiting technology more than other options because

In a regulatory scheme, there is a higher cost to deorbiting because the cost of that fuel to deorbit ends operation of the satellite earlier would be more than what operators are currently doing. This has a massive impact on how effective the program costs are. Different rules may only alter the changes for certain satellites or manufacturers.

This option is moderately feasible because the costs from deorbiting would be a barrier to take on for industry operators and would make it difficult to say if the implementation would be done effectively across all key countries. There are risks that different rules may lead more individuals to follow the Swarm Technologies example and attempt to avoid regulations or ignore them.

Trading Deorbit Years

Setting up an effective deorbit trading scheme relies on the assumption that credit trading is designed responsibility. If only the satellites capable of naturally deorbiting are selling credits, then this option does not fully leverage possible improvements to compliance, it just changes the nature of the problem. The effective design would prevent CubeSat years from being traded for large satellites orbiting above 600km. Under this assumption, compliance based on trading schemes can have a strong impact on improving compliance at a low cost.

Large scale international agreements on CO2 emissions such as the Paris Accords or Kyoto protocol have struggled to gain enough support to yield substantial reductions. Smaller scale reduction credit trading schemes such as the phasedown of leaded gasoline in the 1980s have been impactful at reducing rates of (Schmalensee, R., & Stavins, R. N, 2017). It is estimated that this alternative could increase compliance between 10-30%. Since companies and countries have a considerable stake in the continued access to space and there is a precedent for spending to reduce risk, this option on could improve compliance up to 30% based on the European Union Emission Trading Scheme for Carbon Dioxide effectiveness (Ellerman, Harrison, &Joskow, 2003). Conservative estimates of increases in compliance are based on the California Regional Clean Air Incentives Market (RECLAIM) trading scheme which falls around 8% decreases in emissions (Schmalensee, R., & Stavins, R. N, 2017).

A reduction credit system would be more effective at sustaining long term impacts than a direct cap and trade system which relies on the initial allocation of permits. There will be an incentive for firms with the lowest cost to deorbit and satellites remaining past their time could incentivize many others to deorbit earlier. Creating an entirely new regime for orbital debris allows for much more flexibility as innovations continue to alter the space operating environment dramatically.

There are overhead costs with setting up and designing a scheme that balances each country and industry interests. Kyoto alone was expected to cost billions in its implementation (Molinari, 2006). Again, the U.S. Environmental Protection Agency phase down of leaded gasoline created a program with low enough transaction costs for substantial trade, and environmental impacts to occur after the program is implemented, especially compared to command and control regulatory programs.

Setting up a trading scheme would require a large amount of international cooperation for this to be feasible. Improving compliance through this mechanism would require an agreement for certification and stronger enforcement consequences than currently exist. Unlike climate change, cooperation on space debris should try to avoid being stalemated by withdrawal from key countries. That means getting buy-in from Russia, China, France, and the United States will be the main hurdle for this option. Effective emissions reductions programs rely on stable regulatory and monitoring regimes and that the source of pollution is traceable. Setting up an enforceable mechanism that is acceptable to major space operators may be administratively difficult because an agency for enforcement and penalties would need to be created and mutually agreed upon.

Industry Consortium

There is support across industry for encouraging a safe and operable space environment, in which community-wide social pressure driven by industry-consensus standards could be successful. A consortium could provide strong social forces through consistent meetings and discussion forums. A multi-stakeholder initiative such as the proposed consortium utilizes open channels of communication, confidence-building, exchange and non-manipulative persuasion through communication, learning and argumentation across sectors, actors, and interests (Koechlin and Calland 2009). The consensus building approach can lend itself to mutually beneficial tradeoffs of interests; Susskind's research on industry group argues that it can reduce transaction cost and produce fairer, more efficient, and stable agreements (2006).

If the consortium is effective at doing so based on the U.S. government's Advanced Battery Consortium designed to bring together U.S. car manufacturers to accelerate the range and performance of electric vehicles (Zucchetto, Wilson,   Spaulding, & Clarendon, 1998). Tradeoffs of this strategy include that industry might not go far enough with the creation of their rules. While standards would be consensus-derived, they would be non-binding compared to a status quo of government. Based on subjective comparative analysis it is reasonable to judge <u>that compliance could increase up to 15%</u> based on the effectiveness of the U.S. battery consortium's work.

This option would be <u>extremely flexible to changes and innovation in</u> the industry if new innovators are brought into the group. They would be able to mitigate concerns about new technology and adaptable to future launches through the accountability members would hold each other to their rules.

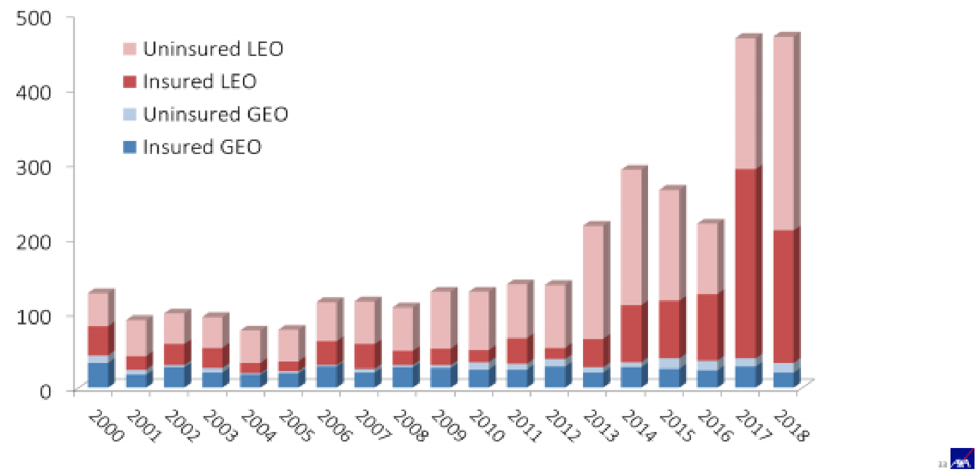
The costs would be <u>distributed among industry</u>, though if a government organization took on the initial organization cost, similar to DARPA in the CONFERS case, then the initial cost would be to individual government. CONFERS is set up so that the U.S. Government funded the startup of the group, with member companies paying dues of $10,000, $5,000 or $2,000 and phasing out government funding as membership increases over time. This model is the basic structure for creating an international industry consortium for deorbit compliance in LEO.

On feasibility, there is much <u>coordination that goes into the start-up</u> of a large multi-national consortium. CONFERS is one already successful example that can be used as a model for start-up, making the process easier. This option requires that stakeholder be involved in the process. It is still one of the more administratively feasible options because similar consortia exist with the space industry and it likely will have support from key players (OneWeb, Intelsat, and others). Politically, this strategy involves industry having a stake participating in the group based on their existing concerns about orbital debris and the safety of their space assets.

Insurance

While insurance may pose opportunities for incentivizing compliance and reducing risk, as shown in Figure 6, many satellites in LEO are not insured, and they comprise a large section of the market. In the future, insurance may be more common in LEO but, even if it is low-cost satellites and constellations are more likely to self-insure than pay into the risk pool (Sundahl, 2000). The actual impact of insurance discounts for those that comply is highly uncertain. As an analogy, The Insurance Research Council found that about 18% drove safer when they received discounts for safe driving based on using telematic devices (2015). [5]

Figure 6: On-Orbit Insurance Status of Satellites Launched in GEO and LEO from 2000-2018



Source: AXA XL Space Insurance, 2018

As far as flexibility into the future, there are several drawbacks. Self-insurance is due to the resiliency in design and the low-cost components from mass production. Since insurance is less likely to be bought for CubeSats or mega-constellations, it has not been considered as a currently viable incentive structure to address the future space environment.

Insurance discounts would have little additional cost since the insurance company could recuperate their loses through reduced risk. Companies would have their cost of deorbiting subsidized through rebates.

Administratively, there is little feasibility because only 50% of satellites in LEO have insurance, meaning insurance underwriters would not currently have enough influence over operators In the analysis, the number of compliant satellites would drastically change if there were more LEO satellites with coverage, that were able to be influenced. In the future, it is likely that as collision risk increases, more satellites will take out insurance which would increase the feasibility of this option. Secondly, the lack of accountability and enforcement of the UN Liability Convention create a moral hazard in the space insurance market, where there is a lack of incentive to guard against risk. In the future, if more countries implement rules requiring on-orbit insurance, tying deorbiting to insurance may become more feasible

[5] Telematic Insurance is a usage-based insurance plans. Insurance companies utilize telematics devices to observe driving habits and tendencies, "tracking drivers' speed, mileage, and total driving time to more accurately determine car insurance premiums" (Center for Insurance Policy & Research, 2019).

Recommendation

Based on current analysis, the strategy with the strongest chance of improving compliance is to form an Industry Consortium for LEO compliance with the deorbit rule. It is politically and administratively feasible because it brings in a group that was not involved when designating the original guidelines and puts the operators in charge of deorbiting at the table. The social pressure and fear of missing out bring many launchers and operators into this group.

There are three key reasons this project is recommended. After overcoming the initial organization and set up costs, the main cost of this alternative will be the actual cost of deorbiting. There is an increased pressure among the industry to act responsibly in space since their profits rely on continued access to space based on the development of norms and previous industry consortiums. Finally, it is adaptable to innovations that are predicted to add 20,000 satellites which allow it to be sustainable in the near future as well as if industry intentions change.

There are strong precedents in the space industry to work off of, and this option applies common property resource governance to bring together key stakeholders in a bottom-up approach to overcome the issues with enforceability. This consortium does not need to be enforceable since industry often works together on projects and can use contracting to push consortia membership and hold each other accountable.

Aerospace Corporation can help stimulate industry interest and bring together stakeholders. There is also a role for beginning collaboration with governments within the United States and elsewhere. Translating the need for compliance with this rule to the general public can also bolster pressure on the industry to begin acting responsibly. The dissemination of information about compliance and promotion of the consortium will help to create buy-in from industry.

Implementation & Future Considerations

For an industry consortium to be as effective as possible, it needs to include the operators and launchers of the future constellations together. The target members would be for prospective constellation operators such as Space X, Boeing, Amazon, One Web, and Iridium to hold themselves to higher standards than 25 years upon the end of life when launching over 1,000 satellites each.

The design of the consortium should include both industry and international government stakeholders. The space industry tends to marginalize startups because of the high cost of entry, but as discussed with the Swarm Technologies example, it is important that start-ups are also engaged. Using CONFERS as a model, it would be best to start with initial government or United Nations funding and phase out the funding as membership grows so that the organization can become self-sustaining through dues. This strategy is not mutually exclusive to the other options and so as concern about defunct satellites grows, overcoming some of the feasibility issues with other options such as insurance, or a trading scheme may become possible as a complement to a compliance consortium.

There is a risk associated with reentry, and it is essential that risk to human life and property from reentry does not increase along with deorbiting rates. If the incentives work, in conjunction with the recommendation there needs to be an increased emphasis on design for demise (burn-up) to prevent an increase in risk. Despite these concerns, controlled reentry holds less risk than uncontrolled reentry. Operators have previously put off the risk of uncontrolled reentry because it will not happen for many years, that does not mean that it is not a concern. Reentry now or later poses a risk but reducing that risk through controlled reentry in combination with lowering on-orbit Collison risk as is expected to outweigh the benefits of waiting to deorbit.

Managing the risks posed by an increasingly congested environment is critical to ensuring safety and sustainability. Improving SSA will allow for actors to have information where behavior can be attributed to individual actors. This creates an advanced peer pressure system and stringent levels of accountability. The process of improving the methods and information sharing network can increase the levels of accountability and verification. Through these systems based on social pressure, it is expected that compliance would also increase, along with the externality of greater availability to avoid an on-orbit collision. Cost is distributed among actors could be within reason, mostly this has not been done because it requires one government to manage a sizeable overhead investment. Having real-time SSA data would revolutionize the verifiability of any deorbit rule.

Increasing compliance and incentivizing lifetime compliance for operators is only part of the solution. Further work should be done on creating viable ADR and profitable systems. Models indicate that debris will continue to grow despite high compliance, mitigation measures, and even in the absences of new launches (Bastida Virgil, B. & Krag, H.). Making active debris removal possible will help bolster compliance. These strategies need to be enacted as complements to each other, not as substitutes. The future of satellites in space and everyday life of the 21st century relies on continued access to space technologies that are threatened by increased launch rates risking an accumulation of satellites in LEO.

> If we are too short-sighted in how we handle the corpses of our machines, they may live on as specters haunting impassable space graveyards – Kyle Hill.

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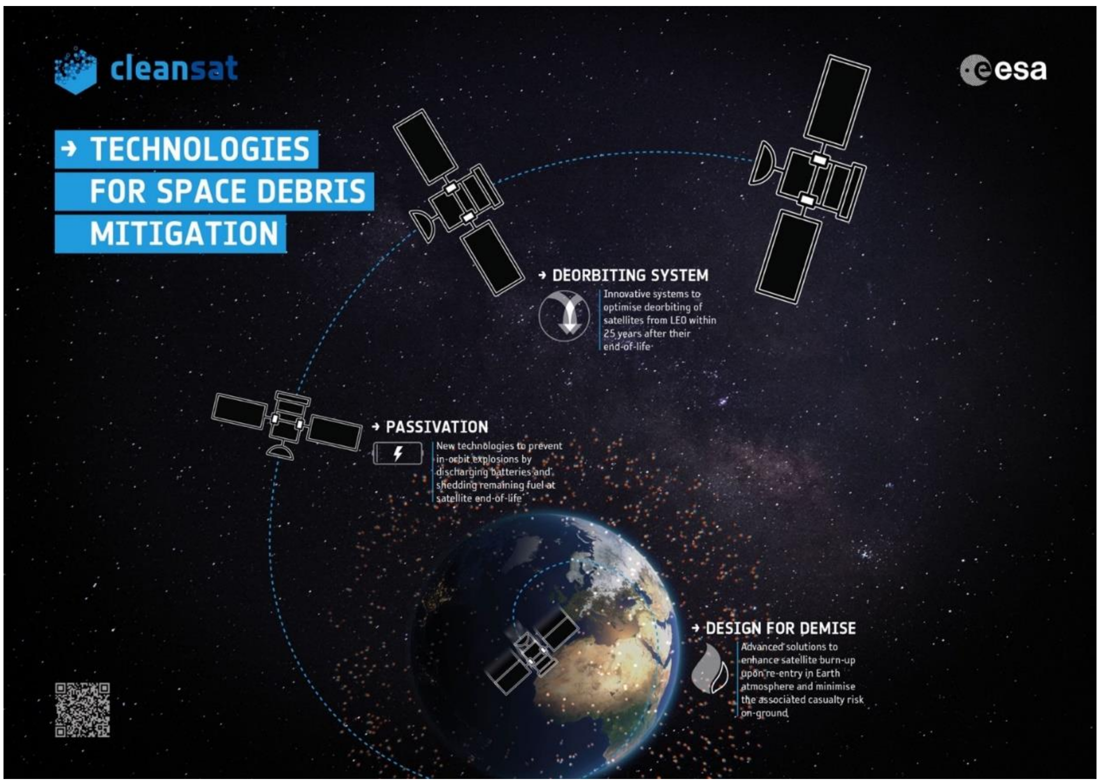
Appendices

Appendix 1: Technical Components of Deorbiting Satellites

There are several difficulties involved with deorbiting satellites that make it both hard to predict their lifespans and to anticipate deorbit timelines. The technical components compound the current issues with enforcement since it is hard to hold companies accountable for what they cannot control. Examples of such limitations include the non-spherical shape of the Earth; the gravity of the Moon, Sun, (and even Jupiter); atmospheric drag at lower orbits; and solar and Earth radiation pressure.. (Nehrenz, M. T., & Spencer, D. A) Atmospheric perturbations and solar cycles, while they have some regularity are very difficult to project out for years, often times those performing Space Situational Awareness do not even have the ability to project where debris will land on earth(Marcos, F., B. R. Bowman, and R. E. Sheehan 2006).

Figure 7: ESA Technologies for Space Debris Mitigation



Source: European Space Agency

The graphic depicted by the European Space Agency explains three components of successful deorbiting a satellite. It is important to remember that satellites must expend fuel to reach an orbit where atmospheric drag and gravity begin to lower them at a fast enough rate to comply within 25-years. Factors that influence deorbiting are listed below:

- Gravity
- Drag
- Upper Atmosphere
- Solar cycles
- Earth's Perturbations

Appendix 2: Cost-Effectiveness Analysis Summary Table

Total Net Present Values of Cost		**Increase from Status Quo**
Current	$1,346,156,597	-
Different Types	$2,257,269,829	$911,113,231.70
Trading	$1,853,525,306	$507,368,708.55
Consortium	$1,375,950,398	$29,793,800.12
Insurance	$1,457,024,556	$110,867,958.50
Total Net Present Value of Satellites Deorbited Over 5-Years		
Current	3669	0%
Different Types	3898	6%
Trading	4605	25%
Consortium	4022	10%
Insurance	3837	5%
Cost Per Satellite Deorbited		
Current	$366,893.47	-
Different Types	$579,082.94	$233,738
Trading	$402,534.12	$110,186
Consortium	$342,070.90	$7,407
Insurance	$379,753.19	$28,969

These results are not sensitive to the discount rate used for future values over five years, tested on a range from 1%-5.5%