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Large Satellite Constellation Orbital Debris Impacts: Case Studies of OneWeb and SpaceX Proposals

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Recent proposals for large constellations of communications satellites have added to the debate surrounding the long-term impact of large satellite constellations on spectrum regulation and orbital debris propagation. The many spectrum license applications currently before the Federal Communications Commission for large, non-geostationary satellite constellation systems provide the satellite risk community with a unique opportunity to weigh the promise of these missions against their long-term impact on the orbital debris environment prior to their launch. The last decade has seen approximately a 60% increase in the total orbital debris object count, and the additional impact of these pending proposals could significantly alter the LEO environment. Furthermore, regulators should examine these proposals within the existing space policy framework to identify potential regulatory inefficiencies. Much of the existing literature focuses on the risk that the orbital environment poses to satellite constellations and distributed spacecraft missions, but the pending constellation requests can serve as case studies for examining the risk that large satellite constellations pose to the orbital environment. Better understanding the proposed systems will offer insight into the risks that mission managers and regulators may be accepting now on behalf the future space community. By examining the licensed OneWeb broadband services satellite constellation and the proposed initial deployment of a similar SpaceX system using the NASA Johnson Space Center Orbital Debris Engineering Model software (Version 3) and a small Monte Carlo analysis, we are able to examine potential implications of the proposed missions, as well as the policy decision space that may emerge as these proposals are reviewed over the coming months and years.

Nomenclature

A	=	Maximum spacecraft cross sectional area (m^2)
L	=	Spacecraft lifetime (years)
$P_{disabling}$	=	Constellation probability of encountering debris greater than 1 centimeter
$Q_{disabling}$	=	Flux of debris greater than 1 centimeter in diameter per square meter per year
ADR	=	Active Debris Removal
DSM	=	Distributed Spacecraft Mission
ESA	=	European Space Agency

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FAA	=	Federal Aviation Administration
FCC	=	Federal Communications Commission
IADC	=	Inter-Agency Space Debris Coordination Committee
ISS	=	International Space Station
ITU	=	UN International Telecommunications Union
JSC	=	NASA Johnson Space Center
LaRC	=	NASA Langley Research Center
LEO	=	Low Earth Orbit
NGSO	=	Non-Geostationary Orbit
OOSA	=	UN Office for Outer Space Affairs
SSA	=	Space Situational Awareness
SSN	=	Space Surveillance Network

I. Introduction

RECENT proposals for large constellations of communications satellites have added to the debate surrounding the long-term impact of distributed spacecraft missions (DSMs) on spectrum regulation and orbital debris propagation. Many of these proposals, including those set forth by OneWeb[1], SpaceX[2], and Boeing[3], provide a unique opportunity to weigh the promise of these missions against their long-term impacts on the Low Earth Orbit (LEO) environment. A pre-launch assessment of the potential impact of these missions can inform discussion of the evolving orbital debris field and possible applications of various debris mitigation strategies, and can provide information to regulators for examining the policy framework governing large satellite constellations proposals. The last decade has seen approximately a 60% increase in the total orbital debris object count, and the additional impact of these pending proposals could significantly alter the LEO environment.

This study investigates the question of impact of large satellite constellations on the orbital debris environment and uses OneWeb, SpaceX, and Boeing proposals as case studies. The remainder of this work is laid out as follows. In Section 2, we provide background information pertaining to the current state of the orbital debris environment, the advent of large satellite constellations, and the existing regulatory framework. In Section 3, we discuss the motivation and methodology for this work, before presenting the results of a simple forecasting experiment in Section 4. Finally, we conclude with a brief discussion and some preliminary policy recommendations.

II. Background

A. Evolution of the Debris Cloud

Orbital debris management is becoming an increasingly urgent focus for engineers and policy makers as large satellite constellations and other proposals related to the commercialization of LEO enter the realm of technical feasibility. The orbital debris environment was first studied at NASA Johnson Space Center (JSC) in the early 1970s, and researchers concluded that any collision between active satellites and orbital debris was highly unlikely.[4] Their work suggested that only objects with a diameter greater than 100 meters faced a significant threat. Subsequent studies based out of NASA Langley Research Center (LaRC) and NASA JSC predicted that the true orbiting population was much larger than the existing catalogued population, which in turn suggested that the collision threat was higher than originally calculated.[4] Fragments from anticipated collisions emerged as potential threats to future missions, particularly those in LEO, where the majority of orbital assets and human missions take place.

The Inter-Agency Space Debris Coordination Committee (IADC), one of several international collaborative efforts attempting to characterize and understand the orbital debris situation, defines space debris as "all man-made objects including fragments and elements thereof, in Earth orbit or re-entering the atmosphere, that are non-functional" and the UN has adopted a similar definition.[5] These objects are tracked and catalogued by a variety of agencies on Earth, including the United States Space Surveillance Network (SSN) and the Inter-Agency Space Debris Coordination Committee, as well as the United States, Russian, and Chinese militaries. The tracked objects generally fall into four categories: fragmentation debris, mission related debris, rocket bodies and launch vehicle upper stages, and satellites.[6] The contribution of each of these categories to the total orbital debris object count is monitored and frequently published by NASA; Figure 1 is from the February 2017 (Volume 21, Issue 1) Orbital Debris Quarterly News, and represents the most recent of these debris field characterizations based on data from the US Space Surveillance Network (SSN). Small pieces of orbital debris, particularly those smaller than a few centimeters in diameter present unique tracking challenges; hundreds of thousands of either undetectable or untrackable objects may be in Earth's orbit but not included within the SSN data, and are therefore not accounted for within this figure.[7]

The last decade has seen approximately a 60% increase in the total orbital debris object count. The two most significant contributors to that increase are the 2007 Chinese Fengyun-1C anti-satellite test and the 2009 collision between Iridium 33 and a defunct Russian satellite, Cosmos 2251. In January 2007, China verified its anti-satellite technology by destroying one of its own failing weather satellites, Fengyun-1C. The resultant debris cloud represented the largest single event increase to the orbital population in history.[8] The impact and policy implications of anti-satellite technology are expansive and beyond the scope of this work, and as such we will not discuss this debris event in great detail here. The 2009 event, however, highlights many of the questions surrounding satellite constellations and orbital debris management.

The 2009 collision between Iridium 33 and Cosmos 2251 was the first major collision between two satellites. Despite ground software estimates suggesting that an approach as close as 117 meters was possible, uncertainty within the calculations prevented a definite prediction of the collision.[2] In fact, data available at the time would not have suggested that this particular approach posed the greatest threat to the 66-satellite constellation in the week preceding the accident. Around the time of the expected close approach, Iridium 33 ceased downlinking information to ground stations on Earth. Shortly thereafter, the United States SSN reported debris clouds in the Iridium 33 and Cosmos 2251 orbits. The collision destroyed both satellites, and generated more than a thousand pieces of orbital debris, 30% of which came from Iridium 33 and became a concern for other satellites within the Iridium constellation that still occupied nearby or intersecting orbits.[9] Improved tracking capability identified additional fragments from the 2007 anti-satellite test and 2009 collision in 2012, shown in Figure 1 as a step increase in total number of tracked objects during that year. Failed launches of both the Ariane and Pegasus launch vehicles, in 1986 and 1995 respectively, also increased the total debris population, as can be seen in the years following the failures, although to a lesser extent than the aforementioned incidents.[10] Gradual orbital decay and atmospheric re-entry over time can result in a decrease in the overall debris count, and voluntary mitigation measures in the early 1980s were successful at reducing the overall population, as seen within the figure.

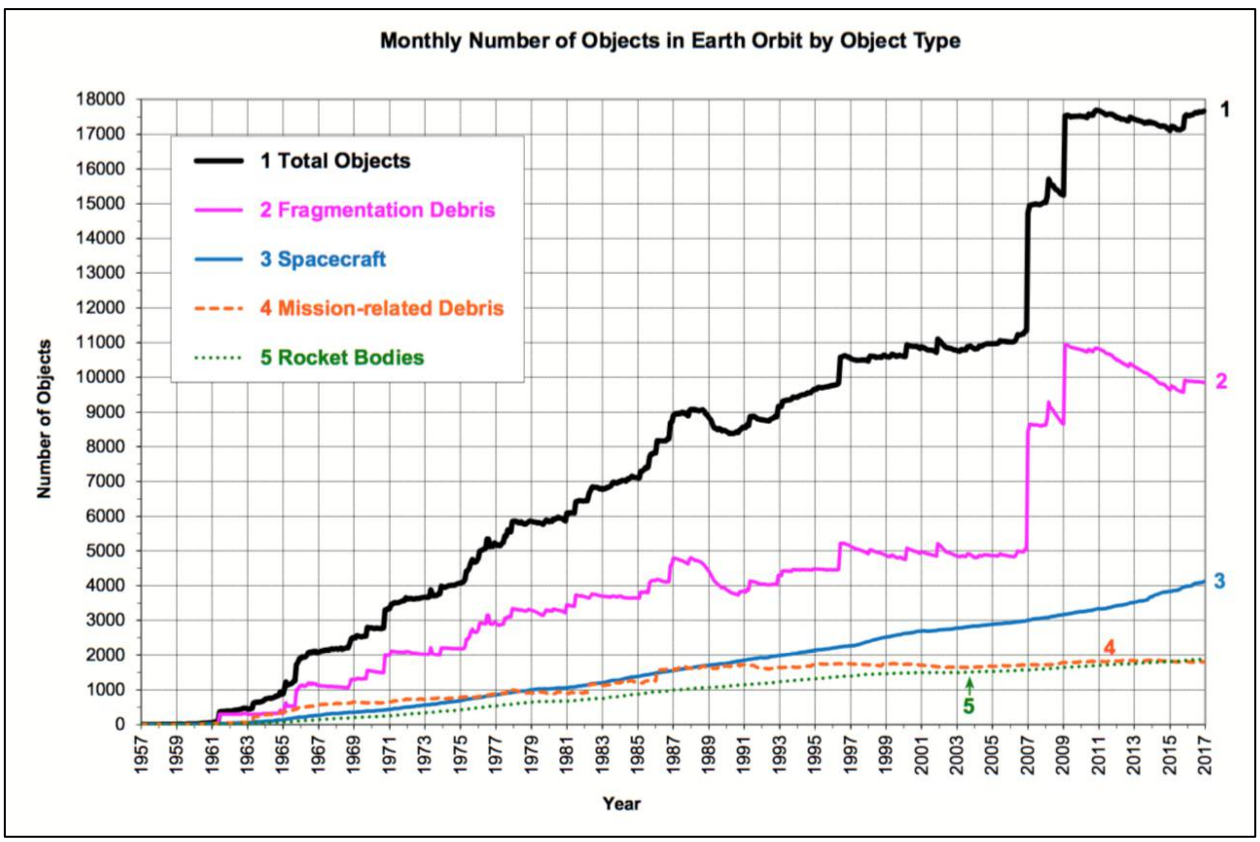

Figure 1. *Orbital Debris Field Characterization. Image Credit: NASA Orbital Debris Program Office, 2017*[6]

The impact of orbital debris collisions largely depends on the size of the debris involved in collision and the speed of the impact. For small pieces of debris, those smaller than 0.01 centimeter in diameter, shielding can be sufficient protection against surface erosion and pitting, but even flecks of paint in orbit have done substantial damage to the Space Shuttle windows and the International Space Station (ISS).[11, 12] Debris ranging from 0.01 to 1 centimeter in diameter can cause impact damage that significantly degrades system performance, and impacts from larger pieces can be catastrophic.[11] Small pieces of orbital debris, particularly those smaller than a few centimeters in diameter present unique tracking challenges, and experts believe that the number of untracked objects in Earth's orbit numbers in the hundreds of thousands.[14]

Novel satellite mission profiles, including the increased prevalence of DSMs and small satellites, have further contributed to the increase in the number of objects in orbit. Small satellite missions, namely those spacecraft with a mass below 1,200 kg, have been identified as a contributing factor to the increase in the number of spacecraft launched between 2012 and 2016, up 53% over the preceding five-year period.[11] Recent estimates suggest there are 1,459 operational satellites (as of December 31, 2016) in Earth's orbit, as well as approximately 670,000 pieces of orbital debris measuring more than 1 centimeter in diameter (as of July 25, 2013), which are sufficiently large to disable a spacecraft upon impact.[13, 14]

B. Advent of Large Satellite Constellations

Distributed spacecraft missions (DSMs) and satellite constellations are those missions which are designed to use more than one spacecraft to achieve a common mission objective.[15] DSMs and constellations offer unique advantages to mission designers, including increased revisit time, coverage area, and sampling frequency, and depending on the architecture design, constellations may offer robustness to the loss of one or more spacecraft. Telecommunications firms have exploited commercial applications of satellites since the 1960s, and constellations began gaining traction as viable options for communication service providers in the 1990s, with the launch of the Iridium and Globalstar constellations.[16]

Recent applications to the US Federal Communications Commission (FCC), which regulates radio spectrum use for domestic spacecraft and coordinates with the UN International Telecommunications Union (ITU) to avoid interference with international spacecraft, have indicated that private firms in the US are aggressively pursuing technologies that would enable large scale satellite constellations to provide unprecedented communications services from space. Filings by OneWeb, Boeing, and SpaceX to implement non-geostationary orbit (NGSO) satellite constellations collectively include thousands of satellites and have raised questions regarding future spectrum regulation and possible orbital debris implications.

Table 1. *OneWeb Constellation Data Summary*[19]

Parameter	Initial Deployment
Phase	1
Total Number of Spacecraft	720
Orbital Planes	18
Satellites per Plane	40
Circular Altitude (km)	1,200
Orbital Inclination (degrees)	87.9
Approximate Mission Lifetime (years)	7
Spacecraft Mass (kg)	150
Spacecraft Cross-Sectional Area (m^2)	3.5

OneWeb filed a petition with the FCC on April 28, 2016, for a constellation consisting of 720 satellites at an altitude of approximately 1,200 km, evenly distributed across 18 near-polar orbital planes. The goal of the constellation is to "provide ubiquitous low latency broadband connectivity across the United States, including some of the most remote areas in places like Alaska where broadband access has not been possible before."[17] Following a round of discussion regarding the petition and input from a range of other satellite operators, the FCC granted the request on June 22, 2017.[18] A summary of the proposed constellation is provided in Table 1. OneWeb has designed several orbital debris mitigation strategies into its constellation design, including a fixture for possible use with future active debris removal (ADR) technologies and fuel reserves for a planned de-orbit maneuver that should remove retired satellites from orbit within two years.[19] Regulators have praised OneWeb's efforts to address orbital debris concerns, but questions remain regarding the concentration of satellites around the Earth's poles and future space traffic management schemes.

The OneWeb filing was the first in a series of similar petitions to the FCC for large satellite constellations aiming to provide broadband communication services. Following the OneWeb application, the FCC solicited proposals from other companies that may be seeking operating permissions in the same frequency bands, triggering a series of follow-on proposals from other private space companies. On June 22, 2016, Boeing submitted a request for permission to implement a network of as many as 2,956 satellites.[3] The massive constellation, which would be installed in two phases, aims to offer global Internet access and was originally designed to operate at the same 1,200 km altitude as the OneWeb constellation. The first phase of deployment would include 1,396 satellites and the second set of 1,560 satellites would be deployed once commercial demand reaches a given threshold. However, in March 2017, the two companies announced an agreement that lowers the Boeing constellation considerably, aiming to alleviate some pressure on space traffic management resources. The proposed solution would place the Boeing satellites in orbits at 1082 km, 1,030 km, and 970 km.[20] Details regarding how the change in altitude might impact other orbital parameters have not yet been made publicly available, and many proprietary details of the spacecraft have not been disclosed given the competition sensitive nature of the data[3] and therefore this information is provided here to provide additional context to the reader. A detailed analysis of the Boeing constellation proposal is not included here, but can be addressed in future work if additional details become available.

Table 2. *SpaceX Constellation Data Summary*[21, 22]

Parameter	Initial Deployment	Final Deployment			
Total Number of Spacecraft	1600	2825			
Phase	1	2	3	4	5
Orbital Planes	32	32	8	5	6
Satellites per Plane	50	50	50	75	75
Circular Altitude (km)	1150	1110	1130	1275	1325
Orbital Inclination (degrees)	53	53.8	74	81	70
Approximate Mission Lifetime (years)	5 - 7	5 - 7	5 - 7	5 - 7	5 - 7
Spacecraft Mass (kg)	386	386	386	386	386
Spacecraft Cross-Sectional Area (m^2)	7.2	7.2	7.2	7.2	7.2

The SpaceX constellation is the largest of the recent proposals, consisting of 4,425 spacecraft with the possibility of an additional two spacecraft per plane (up to an additional 166 spacecraft) to replenish the constellation following any on-orbit failures.[21, 22] A summary of the constellation described by the company in its November 2016 petition to the FCC, augmented with supplemental data gathered from industry news sources, is provided in Table 2. SpaceX has stated the constellation can generate revenue with the installation of the first 800 satellites in the constellation, but will need the full installation to be able to provide complete coverage to the United States. The installation rate itself is highlighting a challenge unique to large satellite constellations; the FCC requires that the proposed system is fully operational within six years of being licensed to prevent companies from occupying, but not making use of, scarce radio spectrum resources. SpaceX and Boeing have already stated that the launch rates that would be required to install their proposed systems within that time frame are prohibitively high. While the FCC is reviewing possible changes to its regulatory framework that would better accommodate large, non-geostationary orbit (NGSO) systems, critics and competitors are urging the FCC to deny the SpaceX petition on grounds that it does not meet the current requirements.[23]

The OneWeb, Boeing, and SpaceX proposals alone represent requests for more than a fivefold increase to the number of operational satellites in Earth's orbit. A summary of these constellation proposals and the percentage increase they represent, with respect to the existing population, is provided in Table 3. These companies are not alone in their interest in the emerging market. Recent reports indicate that, including the 720 already-licensed OneWeb satellites, the FCC is currently considering NGSO applications for a total of 18,470 spacecraft.[24] While the systems proposed could significantly benefit life on Earth, it is not yet clear whether the existing regulatory framework is prepared to support an order of magnitude increase in the number of operational, Earth-orbiting spacecraft. The question of regulatory capability becomes particularly pronounced when considered in the context of orbital debris management.

Table 3. *OneWeb, Boeing, SpaceX Constellation Summaries*

Proposing Organization	Total Number of Spacecraft in constellation (before spares)	Percentage Increase over Existing Operational Satellite Population	Status
OneWeb	720	49.35%	Licensed
Boeing	2956	202.60%	Pending
SpaceX	4425	303.29%	Pending
Total	8101	555.24%	

C. Existing Regulatory Framework

The proposals discussed above have brought the notion of Global Internet closer to realization, and now regulators must confront the tensions arising between existing international space policy, LEO sustainability, and the demands of an evolving commercial industry. We leave these more politically contentious topics to policy makers, but acknowledge that the impact of these large constellations is a complex, sociotechnical problem that will require a great deal of legislative review. Purely from an orbital debris mitigation standpoint, these constellations highlight the need for development within the relevant policy spheres. The notion of orbital debris is widely accepted by spacefaring nations to describe non-functional spacecraft and spacecraft fragments, but there is some ambiguity embedded within this accepted definition. Most of the policy discussion surrounding the classification of an object as orbital debris emphasizes the lack of functionality of the object. However, nations may disagree as to the true meaning of 'functional,' which leaves room for future disagreement, particularly with regard to ADR techniques. Debates could emerge relating to spacecraft salvage value, degraded operating capability, or operations beyond the end of a planned mission lifetime, each of which could present challenges as ADR technologies mature. Many of these technologies also have clear applications as anti-satellite tools, and widespread ADR research has generated substantial debates over topics including the militarization of space and international collaboration, among others.[26] To minimize possible geopolitical tensions surrounding these debates and others related to orbital debris generation and removal, the relevant technology and policy must evolve in parallel.

The fundamental space policy agreements that most notably apply to orbital debris are the "1967 Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies" and the "1972 Convention on International Liability for Damage Caused by Space Objects."[11] These treaties are more commonly known as the Outer Space Treaty and the Liability Convention, respectively.

Article IV of the Outer Space Treaty states that each signatory nation is responsible for its activities in space. Activities conducted either by the state itself or any nongovernmental entities based in that state are classified as the legal responsibility of the launching state's government. The article further states that nongovernmental organizations require authorization and continued supervision by the appropriate national regulatory agent. This provision suggests that any satellites launched by a national government or a private entity headquartered in a given nation are the legal responsibility of the country from which the satellite originated, as are the activities associated with that satellite, including launch, mission operations, and end of life behavior. End of life behavior could certainly be seen to encompass debris generation, and therefore activities that have a high potential to produce orbital debris could be regulated pursuant to Article IV.

Article VIII of the same treaty provides that the launching authority, regardless of the object's presence in space or reentry status, retains the ownership of an orbital object. This has two implications, one pertaining to whether another country can treat a nonfunctional spacecraft as debris without consent of the launching state, and the other pertaining to collision responsibility if the orbital object can be definitively linked to a particular nation. Under the former consideration, even after a satellite reaches the end of its mission life and even without further operational value or control capability, it remains the property of its originator and responsibility of the launching state. This could have significant implications for any ADR efforts pursued without broad international support.[7] The Convention on Registration of Objects Launched Into Outer Space, which entered into effect in 1976, provides a method by which nations can notify the UN Office for Outer Space Affairs (OOSA) of a change in operational status of a given space object[7] and therefore may be an appropriate basis on which to build a formal classification and notification scheme for orbital debris. Such a framework might allow an object to be de- orbited by a state other than the launching state or provide an arena for ownership transfer.

Activities with high potential for orbital debris generation may be further regulated under Article IX of the Outer Space Treaty, which requires signatories to consult the international community if a planned activity would cause "potentially harmful interference" with the activities of other nations or their ability to pursue the exploration and use of space. This places regulators at an important intersection. Activities that could promote economic growth in one country, may threaten the future space activities of another if the debris from the former cannot be sufficiently mitigated. A threshold for "sufficient" mitigation, however, may be difficult to define, and this area is ripe for future research.

The Liability Convention "imposes upon a launching state absolute liability for damage caused by its space object on the Earth or to aircraft in flight" and a space object is defined as "component parts of a space object as well as its launch vehicle and parts thereof" without regard to the functional state of the component.[11] This has direct legal implications for pieces of orbital debris, but the Liability Convention does not clearly indicate which actor is at fault if the damage caused by a component part is inflicted in orbit. If a re-entering piece of debris causes damage to an airborne or ground based asset, the launching nation bears responsibility, but fault or legal responsibility for collisions that occur in space, especially without detailed behavioral characteristics of each object prior to the collision, would be more difficult to assign. The 1995 Interagency Report on Orbital Debris, produced by the United States National Science and Technology Council Committee on Transportation Research and Development, suggests that a form of tort law might be appropriate in this case, but would require the definition of negligence standard that could classify whether control efforts made by the launching state were reasonable to prevent the collision.[11] However, further complications could arise pertaining to the ability of the damaged spacecraft's governing authority to prove a given claim, especially if the collision involves a particularly small piece of orbital debris of unknown provenance. Even very small pieces of debris can cause substantial damage to on-orbit assets.[27] Given these complexities, a purely punitive and reactive legal approach is not likely to be sufficient moving forward as a mitigation strategy.

In 1999, the United Nations published a Technical Report on Space Debris, outlining shielding and collision avoidance strategies, and offered an assessment of the effectiveness of those measures. The report acknowledges that some voluntary mitigation measures implemented in the early 1980s began to successfully reduce the debris population, a conclusion that is supported by the dip in total orbital objects shown in Figure 1. Early mission design that accounts for debris mitigation and de-orbit planning, as well as the limitation of upper stage explosions (e.g. controlled stage de-orbit burns or explosion prevention measures for stages and/or defunct spacecraft with remaining fuel) could be effective in addressing long term orbital debris generation concerns.[28] However, such design efforts are expensive, both through the cost of the design effort and the portion of reserve fuel that must be kept to properly de-orbit a launch vehicle upper stage following payload deployment or a spacecraft following the end of its mission lifetime. In the latter case, this fuel could directly impact the lifetime of the spacecraft by limiting the number of station keeping maneuvers the satellite can execute. Further concerns exist surrounding the reliability of spacecraft that incorporate such efforts, given that they will have low flight heritage and limited capacity for on-orbit testing.

These cost and risk considerations give rise to a "tragedy of the commons" situation, in which there are significant costs borne by the first actor to take steps to protect or improve the environment, while the benefits are shared by all, and so there is limited incentive for any one individual to take the first step toward a solution.[29] It is clear, as recommended by the UN Technical Report and US Interagency Report, among others, that the solution to the orbital debris problem must be international. Efforts are already being made to coordinate initiatives between the United States and China, both of which are major contributors to the number of objects in Earth orbit and which met in June and October of 2016 for workshops on orbital debris and collision avoidance.[30, 31]

NASA, the UN, and the IADC have each published orbital debris mitigation strategies and best practices over the past decades, but a formal, international agreement does not yet exist. Recent efforts that have addressed strategies for orbital debris mitigation directly, include the 2017 "NASA Procedural Requirements for Limiting Orbital Debris and Evaluating the Meteoroid and Orbital Debris Environments" and the 2010 "United Nations Space Debris Mitigation Guidelines of the Committee on the Peaceful Uses of Outer Space."[32, 33] The NASA procedural requirements are mandatory and offer insight into NASA's plan to mitigate United States contribution to the orbital debris population, however assessing the effectiveness of these requirements will take time. Furthermore, recent

European Space Agency (ESA) estimates suggest that approximately 40% of low orbiting satellites do not comply with existing IADC orbital debris mitigation guidelines.[20]

Given that the IADC has no binding authority with which to implement or enforce relevant mitigation requirements, and that the UN and similar international entities have not yet reached a consensus on regulatory frameworks, private space actors have begun developing their own standards. As discussed above, the OneWeb, Boeing, and SpaceX are taking their own steps to reduce orbital debris impact, and OneWeb has openly stated that the IADC regulations are not stringent enough, suggesting that satellites should be required to de-orbit within five years or one times their mission lifetime, whichever is shorter, following their retirement, as opposed to the existing IADC requirement of 25 years.[20]

D. Potential Impact of Large Satellite Constellations on Orbital Debris

Previous research has examined the potential long-term development of the orbital debris cloud assuming current satellite launch rates are held constant, although they are expected to continue to increase. A 2016 study by Bastida Virgili et al. took this a step further, and compared the anticipated orbital debris cloud assuming that end of life mission disposal guidelines (for satellites and launch vehicle upper stages, as proposed by the UN) are implemented with a 90% success rate and the debris cloud that would exist following the launch and subsequent disposal (under the same disposal assumptions) of a hypothetical constellation consisting of 1080 satellites, distributed across 20 orbital planes at 1,100 km altitude. This comparison is demonstrated in Figure 2.

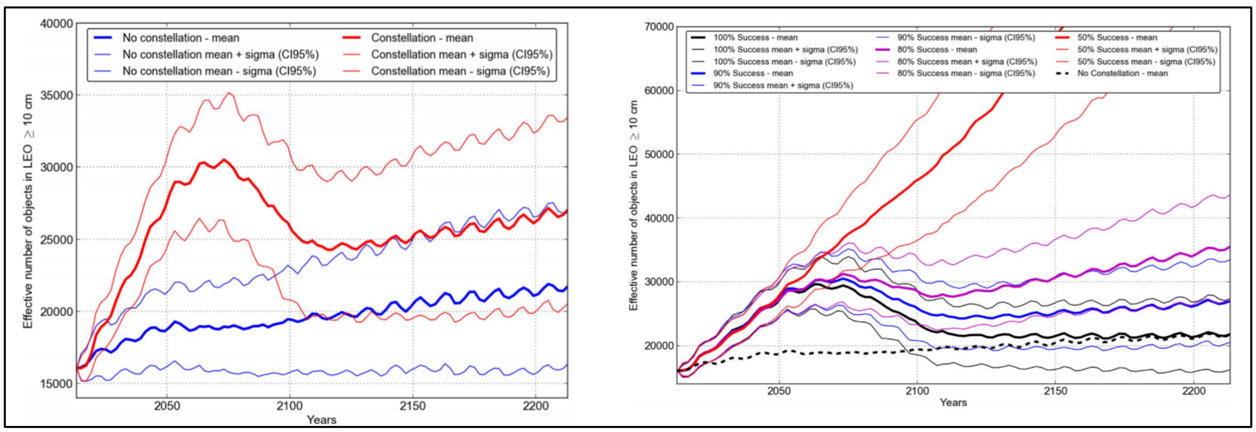

Figure 2. *Comparison of orbital debris environment development without (left) and with (right) hypothetical large constellation. Image Credit: Bastida Virgili et al. 2016*[34]

The debris cloud in the case without the constellation increases gradually over time, in keeping with other similar studies. In the constellation case, the number of objects in LEO increases dramatically, and then decreases as pieces of debris at sufficiently low orbital altitudes naturally re-enter the Earth's atmosphere. Even with this natural debris attrition, the impact of the constellation is significant, showing the addition of approximately 5000 pieces of orbital debris that are greater than 10 centimeters in diameter. As discussed above, objects of this size could cause catastrophic impact damage on other spacecraft, including manned vehicles such as the ISS. Further heightening the severity of this hypothetical situation, the 90% success rate of adherence to disposal guidelines may be optimistic however, and the simulation of the orbital debris environment was also considered for lower disposal success rates. The results, presented for three different disposal success rates, are presented in Figure 3 and indicate that even the introduction of a single constellation could permanently contaminate the LEO environment, and potentially even approach the 'cascading collision' state proposed by Kessler in the 1970s.[7]

It is important to emphasize that 2016 study includes only one large satellite constellation consisting of 1080 satellites, a small fraction of the number of objects that could be launched in the coming decades if any combination of the systems currently seeking launch permissions are realized. This increase in the number of orbital objects could significantly increase the collision risk to other spacecraft, and future ADR efforts could become a necessity, unless policy and regulatory measures are adopted and enforced such that satellites effectively de-orbited after mission completion.

III. Methodology and Analytical Approach

Based on the existing proposals for new, large constellations and regulatory framework, future technology development and policy design will rely heavily on the expected contribution of the licensed constellations to the orbital debris environment. This work seeks to contribute a first step to framing the potential impact of the proposed large satellite constellations on the orbital debris environment, given their proposed orbital parameters. More specifically, we have leveraged an existing model to assess the likelihood that a single spacecraft placed in the proposed orbit for the OneWeb and SpaceX NGSO systems will encounter a piece of debris large enough to fully disable it. We then conduct a simple Monte Carlo experiment to assess the number of encounters each constellation will encounter over its initial operation period. On orbit, these encounters or close approach scenarios may result an evasive orbital maneuver, facilitated by onboard or ground-based space situational awareness (SSA) capabilities, if the debris is large enough to be detected. If an impact with orbital debris cannot be avoided, however, a collision could render the spacecraft inoperable, and the de-orbit maneuvers that companies such as OneWeb and SpaceX have included as part of their orbital debris mitigation plans would then be impossible to execute. In the most optimistic case, such a spacecraft would exist as a single piece of debris, in the spacecraft's original orbit. More realistically, the impact could result in fragmentation and the generation of many pieces of orbital debris within the orbits relevant to the constellation system and could trigger additional impacts. Beginning to assess the risk of such orbital contamination will provide a basis for more detailed analysis and discussion within both the technical and regulatory arenas. The licensed OneWeb constellation and the first phase of the proposed SpaceX constellation are treated as case studies in the following discussion and have been selected for the availability of relevant technical data and pertinence to the current orbital debris discussion.

To model the orbital debris environment that a given spacecraft will likely encounter during its mission lifetime, we have utilized the publicly available NASA Johnson Spaceflight Center's Orbital Debris Engineering Model (ORDEM, Version 3).[35] The software produces the expected orbital debris flux per square meter per year for an input year of observation and given a spacecraft's circular orbital altitude and inclination, using maximum likelihood estimation and Bayesian statistics. The software outputs population fluxes and the associated uncertainties for the input observation year.[36] It should be emphasized that the flux values are expected values, not deterministic values. Because both the OneWeb and SpaceX constellations have proposed operations beginning as early as 2019 and an orbital lifetime of approximately seven years, the observation year for each software trial was set to 2026. The input altitude and inclination for the OneWeb and SpaceX spacecraft are taken from Table 1 and Table 2, respectively. The result from the ORDEM software is converted from the number of orbital debris fragments the spacecraft encounters per square meter per year to the percentage risk of collision for any member satellite within the constellation for a given week during its operating life, based on the proposed cross-sectional area of each spacecraft. We begin by summing expected flux of all debris greater than or equal to one centimeter and up to one meter in diameter from the ORDEM output file. This flux then represents the expected flux per square meter per year of debris large enough to disable a spacecraft. This expected flux of disabling debris ($Q_{disabling}$) is then converted to a probability of collision for the entire constellation. Equation 1 outlines this conversion process, where A is the maximum cross sectional area of a single constellation member spacecraft in square meters, L is the expected mission lifetime of a single member spacecraft in years, and $P_{disabling}$ is the probability of the constellation encountering debris greater than 1 centimeter over its lifetime, subject to certain simplifying assumptions described below. Dividing this probability by 52 weeks per year and multiplying by the number of spacecraft in the cast study constellation yields the threshold value for number of collisions within the complete constellation for a given week during the mission lifetime.

This probability of collision is then used as the parameter of in a simple Monte Carlo simulation in order to estimate the mean and standard deviation of the number of orbital debris elements that the constellation may generate over its initial seven-year operating period. For this paper, 100 samples are used, but future work will increase the number of trials to improve the fidelity of the model. In each sample, a random number is generated for each week of operation and compared to the probability of collision (based on ORDEM output) in order to determine whether or not a collision occurs in that week. If the random number is lower than the threshold, a collision is assumed to have occurred.

$$Q_{disabling} * A * L = P_{disabling} \tag{1}$$

In conducting this experiment, we have made a series of assumptions, which skew the impact of the proposed constellations on the orbital debris environment. First, we assume that each piece of orbital debris and the calculated rate of possible collision events are completely independent for purposes of the model. Secondly, we make a series of assumptions regarding the nature of the collisions between a given spacecraft and any orbital debris. The most fundamental of these assumptions is that the spacecraft are not maneuvered out of the path of an impending collision, even though each of the satellites will have an onboard propulsion system that is designed, in part, to enable these evasive maneuvers. This work is intended to demonstrate possibilities rather than provide conclusive results regarding the impact of these constellations, and a discussion of the specifics of orbital maneuver success rates is beyond the scope of this effort.

Considering the modeled collisions, we assume that each spacecraft is capable of withstanding an impact by any orbital debris less than 1 centimeter in diameter and that such a collision results in no change in performance of the spacecraft. We further assume that for all collisions between a given spacecraft and orbital debris equal to or greater than one centimeter in diameter, the spacecraft is fully disabled, as per the aforementioned ESA metric. The collision is assumed to be perfectly inelastic and generate no additional debris fragments, and therefore each collision generates only one piece of debris. We have also chosen not to consider the possibility that a single spacecraft could be involved in more than one debris-generating event over the course of the constellation's operational lifetime. Third, we have chosen to neglect the impact of the launch manifest on shaping the surrounding orbital debris environment and launch vehicle upper stages placed in orbit as the constellation is installed have not been considered. Finally, we assume that the constellation is in place by 2019, at which time the seven-year mission lifetime begins. This assumption results in a longer orbital lifetime than any of the proposed spacecraft should experience, given the associated orbital debris mitigation strategies. The experiment concludes prior to the attempted de-orbit maneuvers for each spacecraft, and we leave the analysis of the anticipated success rate for these maneuvers for future work. A summary of the input parameters for the two ORDEM trials is provided in Table 4.

Table 4. *ORDEM Trial Input Parameters*

ORDEM Input Parameter	OneWeb Case Study	SpaceX Case Study
Circular Altitude (km)	1,200	1,150
Orbital Inclination (deg)	87.9	53

IV. Results and Discussion

The results of the ORDEM analysis of the OneWeb case are shown in Figure 3, describing the average cross-sectional flux versus the size of encountered orbital debris for a single spacecraft in the defined orbit. Following the procedure described above to simulate the likelihood that any spacecraft within the constellation will experience a collision produces the cumulative expected number of encounters between the OneWeb constellation and orbital debris larger than 1one centimeter in diameter is shown in Figure 4. Similar results for the SpaceX ORDEM trial for a single spacecraft and subsequent forecast experiment are shown in Figure 5 and Figure 6, respectively.

The 100 trial Monte Carlo analysis results show a steady increase in encounters between the constellation in the proposed OneWeb orbit and orbital debris greater than 1 centimeter in diameter over the mission lifetime. The cumulative seven-year average is 17.95 encounters, with a standard deviation of 3.86 encounters, as shown in Figure 4. As discussed above, these encounters represent events that could contribute at least one piece of orbital debris to LEO, if not many more. The service objectives of the OneWeb and other communications constellations will require replenishment of retired or failed satellites to maintain coverage. Launching spares with the initial constellation would make replenishment more straightforward than a targeted launch of a replacement spacecraft, but will also further crowd the initial orbital environment, which could increase the likelihood of collisions within the constellation system.

For the second case, the model indicates that over its seven-year operating lifetime, the initial 1,600 spacecraft within SpaceX constellation will collectively experience approximately 68.42 encounters, with a standard deviation of 8.04 encounters. Given the aforementioned assumptions, the results for both case studies are not conclusive, but rather demonstrations of the potential orbital debris threat to the successful operation of these constellations over their initial operating period. Again, as the spacecraft retire and are replaced, additional encounters are possible, adding further complexity to the associated orbital debris modeling and tracking tasks. If planned de-orbit maneuvers are executed improperly or not at all, such that the spacecraft cannot be fully de-orbited or placed in a safe graveyard orbit, the damaged spacecraft could result in increased collision risk for other spacecraft in LEO, particularly for other operational spacecraft in orbits that intersect the nonfunctional satellite's off-nominal disposal orbit.

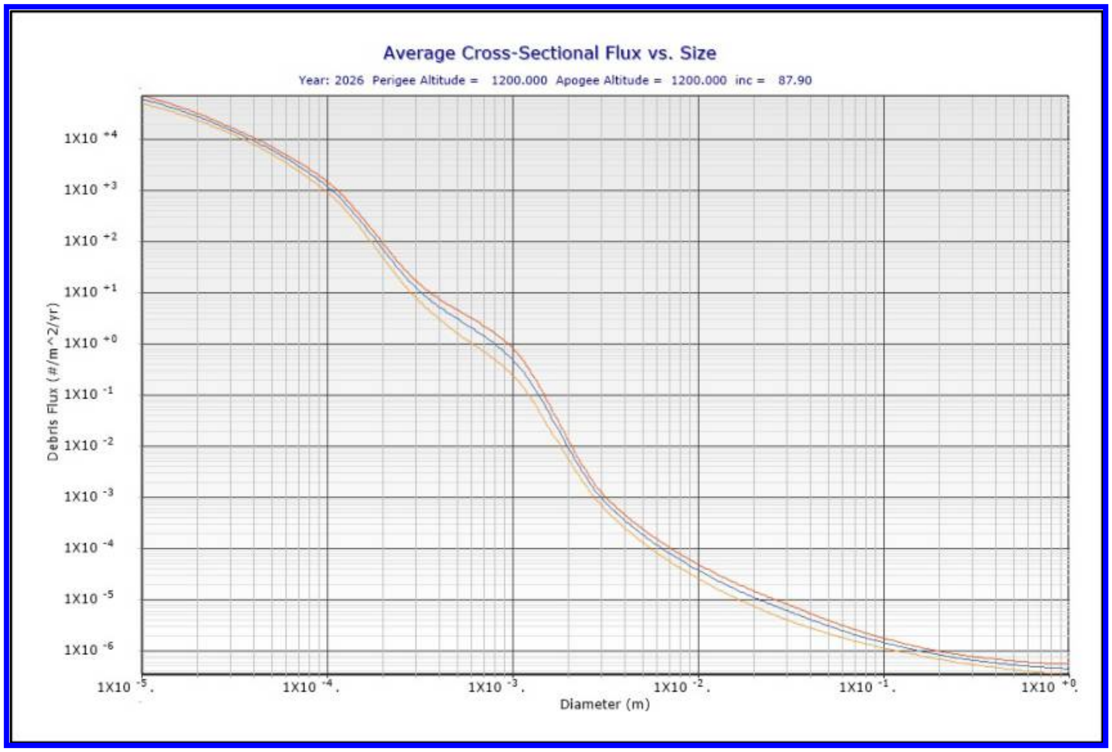

Figure 3. *ORDEM Results, OneWeb spacecraft orbit: Average Cross-Sectional Flux vs. Size, plus or minus one standard deviation*

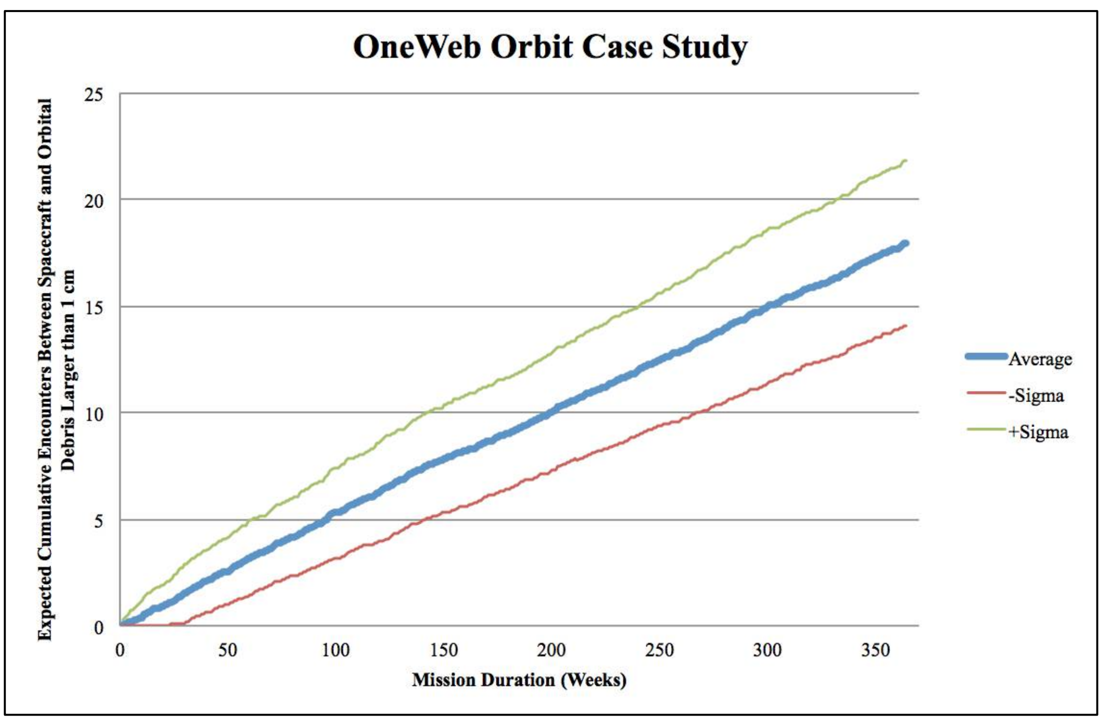

Figure 4. *Model result for proposed OneWeb Constellation orbit*

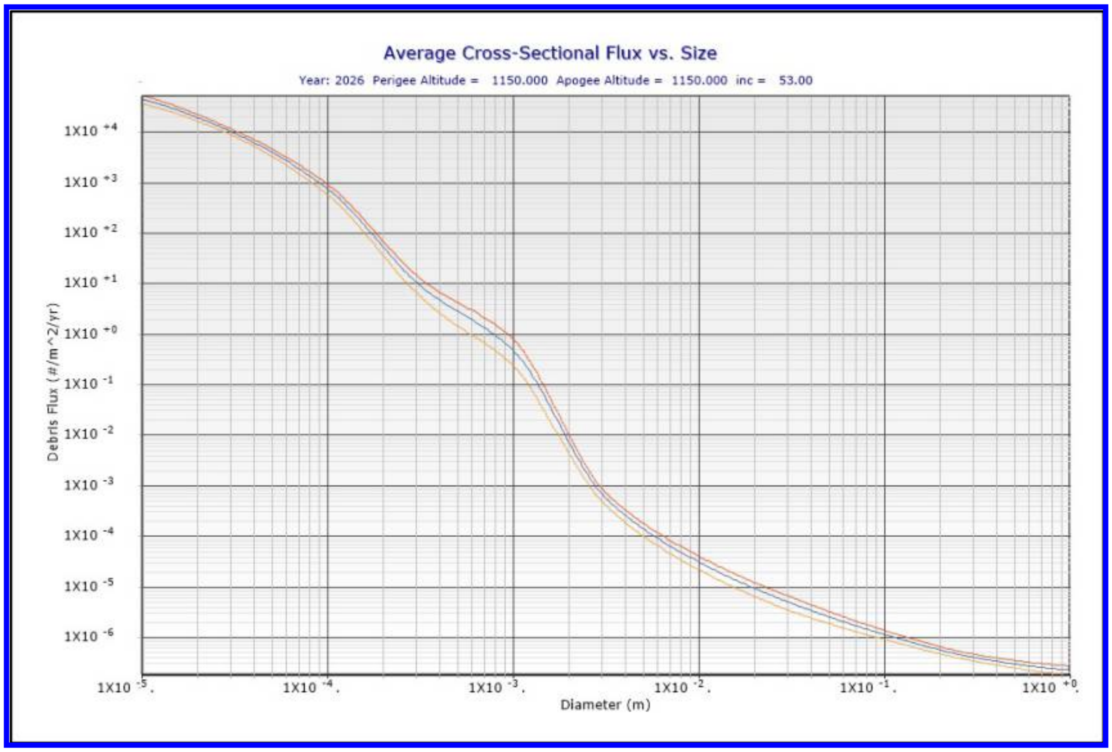

Figure 5. *ORDEM Results, SpaceX spacecraft orbit: Average Cross-Sectional Flux vs. Size, plus or minus one standard deviation*

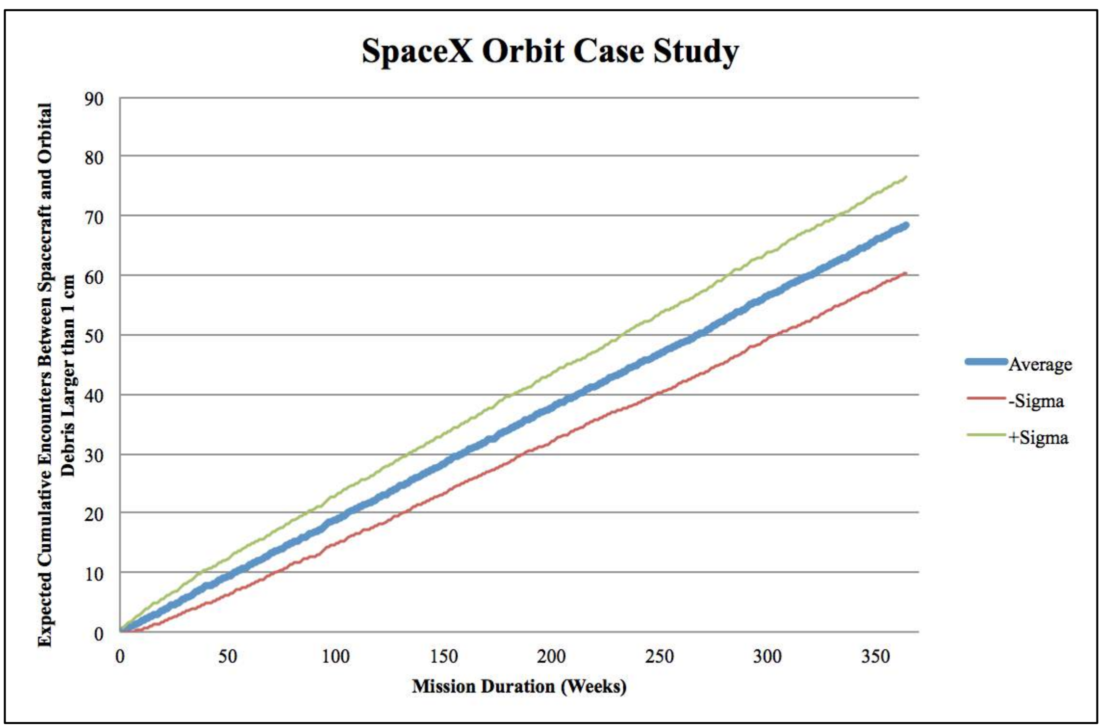

Figure 6. *Model result for proposed SpaceX Constellation orbit*

This analysis also highlights policy and legal implications. Under Article IV of the Outer Space Treaty, debris generated by the proposed constellations, if granted launch and operating permissions by the Federal Aviation Administration (FAA) and FCC, could be considered the responsibility of the United States. This would shift the burden of ADR significantly toward the United States government and NASA. While that would offer an opportunity for the US to lead the way in orbital debris removal, it could also make the US liable for any damage caused by debris generated by these constellations and impacts to future mission planning by any spacefaring nation. The United States could then bear increased responsibility in any future international debris removal efforts. Additionally, as described in the preceding section, this analysis suggests that the United States could have an obligation to consult with other nations before the FAA or FCC can grant launch and operating licenses. Failure to consider the long-term impact of the proposed systems before they are launched, especially without a feasible ADR system available, could be seen as negligent pollution of LEO. Without a negligence standard in place, it might be difficult for the United States to be held liable for future damage, but general adherence to national treaties and best practices is seen as one of the most effective ways of maintaining the space environment.[37] The United States should carefully consider the possible reaction of the international community before ruling on the pending applications, given that the US government will likely be responsible for any possible impacts. However, the existing framework does not emphasize orbital debris generation as an excluding characteristic for proposed missions, and the policy framework must adapt to give these new concerns the appropriate weight within the relevant licensing and certification regimes.

V. Conclusions and Recommendations

The results produced in the preceding section suggest that the orbital debris impacts of the proposed large satellite constellations warrant additional investigation and discussion. While the results are constrained by several simplifying assumptions and are not a high fidelity prediction of the future orbital debris environment, the model indicates that the orbital slots selected for the OneWeb constellation and initial deployment of the SpaceX constellation are likely to expose the constellation member spacecraft to encounters with existing debris large enough to cause a collision. Subsequent collisions beyond these possible encounters and the long term development of the orbital debris field are beyond the scope of this work, but constitute a fruitful venue for future research. While the deployed spacecraft will be capable of maneuvering out of the collision path, unlike the spacecraft within the simple model discussed above, the result of any true spacecraft collision is likely to result in a fragmented debris field as opposed to merely a single piece of debris. The situation is complex and warrants deeper risk analyses to more accurately model the orbital debris field that each of the proposed constellations may face and subsequently generate. The severity of the 2009 collision between Iridium 33 and Cosmos 2251, and the large number of resultant debris fragments, suggests that the consequences of any collision between satellites in these crowded orbits may be extreme.

Beyond the technical challenges that the licensed OneWeb system and other pending NGSO constellations will face, there will likely be additional regulatory hurdles. The technology being used to design and implement large satellite constellation systems has outpaced the existing policy framework, and given that these systems could make a permanent impact on orbital environment, regulators should take this opportunity to work with technologists and system architects to define an efficient and effective governing framework. The proposed systems could offer substantial benefit to users on Earth, therefore simply prohibiting the adoption of NGSO systems is not a viable solution.

In light of the discussion presented within this work, preliminary policy recommendations can be made regarding both domestic and international strategies for addressing orbital debris concerns. For domestic recommendations, we can consider where orbital debris management might fit into the existing regulatory framework. The first recommendation is that the FCC should consult with NASA and assess the remaining pending applications not only against the possibility of radio operating interference but also against long-term debris impact of the proposal. Given the FCC's stated mission to promote "competition, innovation and investment in broadband services and facilities" within the United States, the FCC is certainly an essential portion of any future NGSO regulatory framework.[38] However, challenges may emerge for large constellations, such as the Planet imaging constellation, that are not focused on communications infrastructure but require similar regulation, beyond the jurisdiction of the FCC. This gives rise to the second recommendation. The Office of Commercial Space Transportation within the FAA should study and evaluate the impact of each of the large satellite constellation proposals against the 2017 NASA Debris Mitigation requirements before the FCC takes further action regarding these proposals and provide the results of this study to Congress, the FAA, and the FCC. Congress could leverage this information to justify legislative changes to the existing licensing regime, and plans should be made for managing the impact of United States government and industry activities on the orbital environment. A third, longer term recommendation, is that the United States should develop a formal assessment and review capability for proposed missions before development begins, and this review agency should interface directly with the UN Office for Outer Space Affairs. This assessment capability should augment the existing US Government Orbital Debris Mitigation Standard Practices as necessary for innovative technologies.

From an international perspective, the United States should pursue international partnership efforts to demonstrate active debris removal technologies, and work closely with OOSA and any interested nations, including China as permitted by Congress, especially given the impact of the 2007 Chinese anti-satellite test. The pursuit of an ADR technological demonstration mission with a wide variety of international partners, and with the support of OOSA, could give each nation a voice in the form of future ADR efforts and protect its existing and future space.

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