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Responsible Behavior for Constellations and Clusters

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Many large constellations are being considered for deployment over the next ten years into low earth orbit (LEO). This paper seeks to quantify the risks that these constellations pose to the debris environment, the risks that the debris environment poses to these constellations, and the risks that these constellations pose to themselves.

The three representative constellations examined in detail in this paper are operated (or planned to be operated) by Spire Global, Iridium, and OneWeb.

This paper provides a balanced risk analysis including collision risk, operational risk, and non-adherence risk. For perspective, the risk posed by these economically useful constellations is compared to the risk associated with existing abandoned hardware deposited in clusters.

INTRODUCTION

Various national and international agencies are looking into the issues of space debris and space traffic management today. The United States (U.S.) Congress passed the U.S. Commercial Space Launch Competitiveness Act in November 2015 (the "Space Launch Competitiveness Act"), which among other things, ordered a study seeking "[r]ecommendations related to the appropriate framework for the protection of the health, safety, and welfare of the public and economic vitality of the space industry." [1]

In response to this request, the Science Applications International Corporation delivered the Orbital Traffic Management Study Final Report to NASA on November 21, 2016 (the "Traffic Management Study"). Section 839, Orbital Debris, of the NASA Transition Authorization Act of 2017, S.442, 3 Jan 2017 reads: "Congress finds that orbital debris poses serious risks to the operational space capabilities of the U. S.; an international commitment and integrated strategic plan are needed to mitigate the growth of orbital debris wherever possible…"

Of course, space debris is a global issue that must be addressed globally. Of the approximately 23,000 catalogued space objects (greater than 10cm), only 6% are operational and only 1.7% are U.S. commercial spacecraft. [2] Internationally, the Committee on the Peaceful Uses of Outer Space (COPUOS) issued draft guidelines for the long-term sustainability of outer space activities in October 2016, [3] which were discussed in depth at the February 2017 meeting of COPUOS in Vienna. The European Space Agency held its 7th European Conference on Space Debris from April 18-21, 2017 where much of the focus was on constellations and how the constellation operators should be regulated relative to "typical" space operators. Many countries are grappling with whether, when, and how to address orbital debris concerns such as debris mitigation and debris remediation whose importance are both accentuated when considering the deployment of large constellations.

In short, this is a very critical time with respect to orbital debris issues. A time during which the regulations that govern satellite operations for the next 10-20 years will be promulgated. We agree with the Traffic Management Study that "[i]t is of critical importance that any policy adopted and any rules, regulations, standards, and operational requirements established are firmly based on physics, technical considerations, and operational limitations and timelines…." and that "[p]olicies and operational requirements that are not sufficiently based on informed physics and technical considerations will no doubt create economic consequences, while potentially *not* mitigating safety risks significantly." [4]

We hope that this paper provides a broad and balanced perspective for thinking about the "wide spectrum of risks" posed by and to constellation operators. This, in turn, should help inform carefully considered rules and regulations that mitigate practical orbital debris concerns, while not stifling the economic vitality of the satellite industry.

BACKGROUND

This paper evaluates a range of risks including collision, operational, and non-adherence risks. This paper does not just focus on the risk of a constellation to the environment, but also seeks to provide an assessment of the potential hazard of the LEO environment on the constellation in question and also of the constellation in question on itself (i.e., fratricide).

We conduct this balanced risk analysis on three representative constellations over the next 10-20 years; anything beyond that has growing uncertainties from practical (i.e., new technologies available), financial (i.e., changing economic market conditions), and physical (i.e., different solar cycles) perspectives. Longer term predictions will lack the needed reliability and accuracy to be actionable. It is important to complete an analysis that is relevant to current rule making, operational tradeoffs, and debris mitigation activities and not just producing academic, non-actionable long-term observations.

The three representative constellations analyzed in this paper are Iridium's legacy constellation, OneWeb's planned Fixed Satellite Service (FSS) constellation, and Spire Global's current LEMUR-2 constellation. These constellations, in the aggregate, provide a representative sample of the types of satellites to be deployed into LEO over the next 10-20 years.

First, Iridium has been operating for 20 years providing an historical record of a LEO operator and the risks that constellation operation poses to, and faces from, the debris environment and itself. It has station keeping capabilities, inhabits a relatively spatially dense orbit (~780km), is moderate in mass (~40,000 kg in aggregate), is moderate in areal cross-section (~300m^2 in aggregate), and is less numerous (72 satellites) compared to many proposed constellations. It is also representative of Iridium NEXT, the replacement constellation being launched over the next few years that will be around for another approximately 20 years.

Constellation management for Iridium is eased by having all satellites with similar orbital periods and altitudes. Looking at the publically-available Joint Space Operations Center (JSpOC) satellite catalog, the "thickness" of the operational constellation (i.e., altitude span) is only 6km (773-779km).

Second, OneWeb proposes a large FSS comprising 720 satellites [5] in a high LEO (1200km) orbit that typifies the large FSS constellations proposed by other operators such as SpaceX, Boeing, and Telesat. Like Iridium, OneWeb will have station keeping but has selected a relatively sparsely populated orbit (~1200km), is high in mass (~108,000kg in aggregate), high in areal cross-section (~2,500m^2 in aggregate), and it will be much more numerous than Iridium (~720 vs ~72 satellites). OneWeb is quite relevant as it, along with similar planned FSS constellations, is being launched and will operate over the next 10-20 years. It is assumed that OneWeb will have a much larger "thickness" than Iridium based on its FCC filing. The constellation was said to be contained within 1% of its semi-major axis, so ±75km for a total width of 150km centered at 1200km.

Third is Spire Global's LEMUR-2 constellation. Spire Global is in the process of deploying a 175-satellite constellation in the 400-600km altitude range comprised of 3U CubeSats. 3U CubeSats typify the most common type of small satellite being launched today and which are expected to be launched over the coming years. [7] Over the next seven years, SpaceWorks estimates 2,400 nano/microsatellites will require launch or 342 per year on average. [6] However, estimates based on 15 year license terms and/or aspirational operator plans tend to be very optimistic.

For instance, SpaceWorks's original 2016 Nano/Microsatellite Forecast of 210 satellites estimated to be launched in 2016 was off by nearly 50% with only 101 nano/microsatellites actually launched. [8] LEMUR-2s will deploy to relatively less spatially dense orbits of 400-600km, are low in mass (875kg in aggregate), low in surface area (16m^2 in aggregate), and will lack station keeping. Spire, as more of an ad hoc constellation, will naturally have a "thicker" altitude span for the constellation (i.e., ~200km).

In summary, the three constellations analyzed in this paper provide a very representative sample of the types of operating satellite constellations that may populate LEO in the coming decades. We now turn to a balanced risk analysis of each of our representative constellations. Table 1, provided below, summarizes qualitatively some of the characteristics of the three constellations examined in this paper relative to each other.

Now, we will develop relationships for collision risk that will be used to characterize risks related to these three constellations.

Table 1. The three constellations being examined in this paper comprise three typical constellation types.

Name	Type	Background Debris Hazard	Operational Thickness	Aggregate Mass	Aggregate Areal Cross-Section	Number	Station Keeping
Iridium	Historic LEO	High	Thin	Moderate	Moderate	Moderate	Yes
OneWeb	New FSS	Low	Moderate	High	High	High	Yes
Spire	CubeSats	Low	Thick	Low	Low	Moderate	No

COLLISION RISK

Risk to the debris environment from collisions is probability multiplied by consequence. We will first examine probability and then consequence. The probability of collision for a satellite from the background debris hazard is given by:

$$PC = 1 - \exp^{(-SPD \times VR \times AC \times T)}$$

Where PC = probability of collision for T
SPD = spatial density, number of debris per cubic kilometer
VR = relative velocity, km/s (10km/s average in LEO)
AC = areal/collision cross-section, km^2
T = time, seconds

The full development for this expression is provided in Appendix A. While much focus is on the operational phase of a satellite's orbital life, there is a significant phase on each side of operations, deployment and disposal, that are often overlooked. During both phases there may be a significant risk posed to or from these constellations. The higher the operational altitude, the more transit time and exposed area to the background population will accumulate during both deployment and disposal. In addition, for disposal it is very relevant how long the operators will maintain control of their satellites.

More pointedly, if a retiring satellite is left to be removed by atmospheric drag (i.e., maneuver capability no longer functions) then these satellites would be unable to avoid collisions with trackable objects or direct reentry to an ocean (i.e., a sparsely populated area of the globe).

Given that the primary variable in determining probability of collision is spatial density of existing resident space objects (such as debris fragments and derelict hardware) of an orbit, we must first examine the spatial density of orbits where Iridium, OneWeb, and Spire constellations (will) transit and reside.

Background Spatial Density

The figure below shows the deployment locations for each constellation overlaid on the spatial density curves as derived from NASA's ORDEM engineering model provided by Mark Matney of NASA/ODPO. Throughout the analysis, we will be using the >1cm threshold to represent the lethal yet nontrackable (LNT) debris and the >10cm threshold to represent the cataloged population which is trackable and potentially avoidable, if a satellite has maneuver capabilities and successfully executes a maneuver.

A 1cm impact would likely severely disrupt or terminate the operations of a functioning satellite while a trackable object (represented by the >10cm population) would likely not only terminate the mission of a functioning satellite but probably cause the satellite to completely fragment.
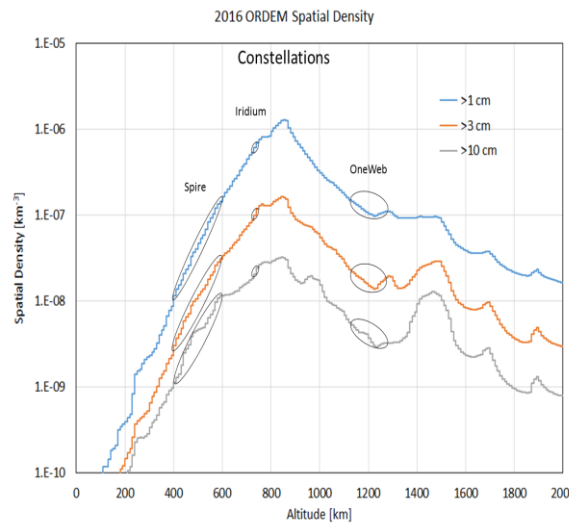

Figure 1. The locations of the three constellations are plotted on the spatial density curves for orbital debris in LEO.

Probability of Collision

The table below quantifies the probability of collision of each *constellation* during its respective deployment, operations, and disposal phases.

Neither deployment nor disposal are relevant for the Spire constellation since these CubeSats operate where they are deployed and are removed from orbit via atmospheric drag. Both OneWeb and Iridium nominally will have their satellites deployed initially at ~500km but the deploy operations for Iridium satellites is much shorter due to the proximity of their lower operational altitude (~780km vs ~1200km for OneWeb).

For OneWeb, the current conops is that once the spacecraft is verified as sound, it will use its electric thruster to transit the most densely populated portion of LEO to achieve its ~1200km operational orbit in about six months. The intent of this deployment plan is to ensure that no satellites are dead on arrival (DOA) at 1200km where they would linger for over 100 years. However, the transit does itself pose a non-trivial collision risk to the constellation, as seen in the table below.

Assuming all goes to plan, this deployment transit poses little risk to other operational satellites since OneWeb has the capability to avoid cataloged objects. Of course, a disabled OneWeb satellite in any part of the transit then poses a background debris risk to other satellites in that orbit. This long transit does raise at least three questions:

- If a OneWeb satellite and another operational satellite are warned of a potential close approach – who must move? Should the satellite whose orbits are being crossed have the "right of way" during OneWeb's elective journey to 1200km?
- Is the risk imposed by the OneWeb transit higher or lower than the risk of deploying a DOA satellite at 1200 km? And, to whom?
- Is a DOA satellite lingering for a long period at 1200km safer or more risky than a DOA satellite lingering for a shorter period at 500km?

Iridium's disposal plan is to lower the perigee of 10 of its satellites to 600km then rely on atmospheric drag to de-orbit these satellites within 25 years and lower the perigee of its remaining satellites to 250km. [9] OneWeb's disposal plan is to lower the perigee of its satellite's orbit to 200km and de-orbit from that altitude, effectively transiting back through LEO, a process they estimate will take less than one year. [10]

OneWeb hopes to maintain active control all the way to reentry minimizing the possibility of debris landing on populated areas. For Spire, the current concept of operations is to naturally decay from its operational orbits using atmospheric drag, thus its

Table 2. Probability of collision values for all phases of the three constellations are detailed below.

Cluster/ Constellation	Number of Satellites	Altitude and Span (km)	Single Satellite Cross-Section / Mass	Total Aggregate Cross-Section	Deployment		Operational Collision Risk / Year (1cm / 10cm)	Disposal	
					Start Altitude and Duration	Probability of Collision (1cm / 10cm)		Time to Dispose	Probability of Collision (1cm / 10cm)
Iridium	72	776 ± 6	4m^2 560kg	~300m^2	500km 1mo	4.4E-3 [1.1E-4]	0.07 [1.8E-3]	5-15yr	~0.4 ~0.05
OneWeb	720	1200 ± 75	3.5m^2 150kg	~2500m^2	500km 6mos	0.20 [7.1E-3]	0.15 [4.8E-3]	1 yr	~0.30 [1.4E-2]
Spire	175	500 ± 100	0.09m^2 5kg	~16m^2	N/A	0	3.2E-4 [4.3E-5]	~5yr	~1.5E-3 ~2.0E-4

probability of collision for disposal is the same as for its operational phase.

The PC/yr for operations for the total constellation for Iridium and OneWeb are within a factor of three; whereas Spire is orders of magnitude lower. Iridium is located in a more densely populated region but the OneWeb constellation has a greater aggregate cross-sectional area. Iridium is clearly operating at an altitude that presents the highest probability of collision with regard to debris, partially due to an earlier Iridium collision. Interestingly, deployment of the OneWeb constellation over six months exposes it to greater PC than a full year of operations. Disposal of OneWeb satellites poses the greatest PC as their transit is twice as long (nominally) as deployment.

The collision risk during operations will fluctuate for Spire based on the solar cycle while OneWeb's collision risk should stay constant unless debris-generating events happen near it. A large debris generating event at 1200km will materially change the orbital environment and increase the probability of collision for many decades because atmospheric drag at 1200km has little effect. We address the impact of this fratricidal case below.

For Iridium and OneWeb, the PC with objects > 10cm is listed in brackets. The number given represents probability based on raw calculations without regard to a satellite's ability to maneuver to avoid these collisions. The actual probability of such satellites having a collision during their operational lifetime given their propulsive capabilities is one that should be studied in more depth. On the one hand, one would hope that given the ability to maneuver around trackable objects the collision probability should be lower than one derived solely from surface area and spatial density calculations.

On the other hand, satellites cannot maneuver around LNT fragments which can disable them making them non-maneuverable. In addition, satellites that are put into disposal orbits cannot maneuver during the disposal portion of their orbital lifetimes, which for Iridium would be as long as its operating lifetime in some cases. Finally, Iridium 33 has shown that the probability of collision with trackable objects is certainly not zero. Given the PC/yr in Table 2, there is a 3.5% chance over 20 years a collision with a trackable object would occur. In fact, we know about one Iridium collision with a trackable object over the past twenty years given that they had about 70 operational satellites implies a 1.4% probability of failure (i.e., 1/70 over 20 years). We discuss below some of the reasons why propulsion is no panacea

under "Operational Risk". This is certainly an area that requires more study as it is evident that much of the collision risk is due to human interactions and not purely based physics models.

Consequence

The table below provides an assessment of the consequence if a satellite of each of the representative constellations fragments completely due to an explosion or collision with a cataloged debris fragment (i.e., the amount of debris created is proportional to the mass of the respective satellite). For each event, there will be 1.5 trackable fragments per kg of mass of satellite and 15 LNT per kg of mass of satellite created. These fragments will largely be spread above and below the center of each constellation by 100km (so a total spread of 200km). The debris will reside more near the center of the resulting debris cluster: 40% of the fragments in the middle 50km and 75% within the middle 100km. The spatial density in the table above represents the middle 50km; the densest part of the resultant debris cluster. The last column depicts the contribution of this newly created debris relative to the existing debris population at the operational orbit of each of our constellations. For example, a value of 0.5 means that the spatial density would be increased by 50% if such a fragmentation took place.

Table 3. The consequence of a satellite fragmentation within each constellation is proportional to the mass of a member of each constellation.

	Fragments		Spatial Density		Relative to Debris Background at Operational Orbit	
	>10cm	>1cm	>10cm	>1cm	>10cm	>1cm
Iridium	840	8,400	1.1E-8	1.1E-7	0.53	0.13
OneWeb	225	2,250	2.5E-9	2.5E-8	0.36	0.25
Spire	7	70	2.4E-10	2.4E-9	0.03	0.03

What can be seen from the above table is that for any one catastrophic collision of a satellite in one of the constellations studied in this paper, Spire's LEMUR-2 satellites have the least consequence relative to the debris environment (and its own orbit). A breakup in the Iridium constellation has the greatest effect (due

to the larger spacecraft). Adding the consequence of a certain number of catastrophic collisions within the various constellations back into the collision risk is helpful in understanding the consequence of catastrophic collisions within these constellations on themselves. It should be noted that Iridium is already at the worst possible altitude (partially due to a previous collision involving an Iridium satellite) and so a 53% increase from another Iridium collision is more significant than a 36% increase from a OneWeb collision.

Another way to look at this this fratricide effect is to examine the ratio of the number of trackable debris fragments produced (shown above in Table 3) by the number of satellites in the constellation. The results of this are shown in Table 4 below highlighting that a destructive event is proportionally worse for the Iridium constellation and least impactful for the Spire constellation.

Table 4. A debris–generating event would be proportionally worse for the Iridium constellation and least impactful to the Spire constellation.

	Trackable Fragments from Destruction of Member	Members of the Constellation	Ratio of Fragments Produced to Members of Constellation
Iridium	840	72	~12
OneWeb	225	720	~0.3
Spire	7	175	~0.04

PERSPECTIVE

While the number of satellites in these constellations creates large aggregate areal and mass characteristics

in comparison to even monolithic GEO satellites, there are existing groupings of abandoned resident space objects that are more troublesome to future debris growth than any of the three constellations reviewed.

Three clusters of massive derelict objects will now be detailed and compared to the three constellations. Each cluster is named by the center altitude of each cluster (e.g., C850 is a cluster centered around 850km). A cluster is defined as a set of space objects with identical inclinations and similar altitude. Empirical analyses have shown that the members of these clusters interact with each other more than modeled by the probability of collision equation presented earlier that is based on the kinetic theory of gases.[11] Note that each cluster is comprised of a set of rocket bodies (RB) and the payloads (PL) that the RBs deployed.

Table 5 below provides some key characteristics of these three clusters relative to the three constellations being analyzed. Table 6 below provides the probability of collision values for the entire cluster or constellation. OneWeb and Iridium values are in brackets for the reasons discussed above.

Tables 5 and 6 highlight the very probable large number of impacts from LNT over the long-term. These types of impacts will trigger anomalies to the operational spacecraft and bursts of small number of more LNT from non-debilitating impacts on constellation members but much more so from the clusters of massive derelicts.

Table 5. Comparing the three constellations against three clusters of massive derelicts provides a perspective on the criticality of these disparate space hardware collections.

		Number of Objects	Ave cross-section (m²) / mass (kg)	Total Area (m²)	Total Mass (kg)	Altitude Span (km)	Annual Inter-Cluster Collision Rate	Cataloged (LNT) Fragments from Collision Event
Cluster	**C775**	89 (45RB & 44PL)	RB: 14/1434 PL: 6/800	900	~100,000	60	~1/500	~4,500 (~45,000)
	C850	36 (18RB & 18PL)	RB: 44/8300 PL: 8/3250	936	~208,000	45	~1/1200	~16,000 (~160,000)
	C975	286 (144RB & 142PL)	RB: 14/1434 PL: 6/800	3,000	~560,000	85	~1/120	~4,500 (~45,000)
Constellation	**Iridium**	72	4/560	300	~40,000	6	N/A	~1,600 (~16,000)
	OneWeb	720	3.5/150	2,500	~108,000	150	N/A	~450 (~4,500)
	Spire	175	0.09/5	16	875	200	N/A	~14 (~140)

Table 6. The probability of collision calculations for each of the constellations and clusters highlights the enormity of both collections of space hardware.

Red:~10⁻¹ Black:~10⁻² Grey:<10⁻²				Total Constellation/Cluster					
				>1cm			>10cm		
Name	Altitude (km)	SPD 1cm	SPD 10cm	PC 1yr	PC 10yr	PC 20yr	PC 1yr	PC 10yr	PC 20yr
C775	775	8E-07	2E-08	0.2031	0.8967	0.9893	0.0057	0.0552	0.1073
C850	850	1E-06	3E-08	0.2556	0.9478	0.9973	0.0088	0.0847	0.1623
C975	975	3E-07	2E-08	0.2471	0.9415	0.9966	0.0187	0.1724	0.3151
Iridium	776	8E-07	2E-08	0.0701	0.5164	0.7662	[0.0018]	[0.0180]	[0.0357]
OneWeb	1200	2E-07	6E-09	0.1470	0.7960	0.9584	[0.0048]	[0.0466]	[0.0910]
Spire	500	6E-08	8E-09	0.0003	0.0030	0.0059	0.000040	0.0004	0.0008

It should be noted these three clusters amount to about 20% by mass and number of derelicts in LEO so this continual interaction may become relevant over the long-term as massive non-operational objects continuously create large numbers of more LNT. Don Kessler even raised this potential concern for a cascading of small, but destructive, debris to be more likely and more imminent than the classic Kessler Syndrome he has been known for. [12]

Now for some perspective on consequence from Table 6. A collision in C850 will have the greatest consequence as the rocket bodies in C850 are SL-16s that have a mass of 8,300kg with a length of 11m and diameter of 3.9m. If two of these were to have a hypervelocity collision then about ~16,000 trackable fragments would be created. This would double the cataloged population in one instance. The payloads that occupy C850 with the 18 SL-16s have masses of 3,250kg; a collision between them would also likely create ~16,000 large fragments..

Alternatively, C975 has the greatest probability with nearly 300 derelict objects spanning only 85km. In addition, if a collision occurs in C975 or C850 the resulting debris will remain in orbit many decades while debris from C775 collisions will likely have significant wash out over a few decades. Collisions in C975, while not as severe as the C850 collisions, will still likely create about 4,500 trackable fragments.

This would make it one of the top three breakups ever and there is a 1/120 chance (i.e., ~1%) each year of such an event occurring. The C850 inter-cluster annual collision rate is smaller but is still 1/1200 (~0.1% per year).

As discussed earlier, the effects of drag are critical in considering the lingering risk posed by debris production. The figure below shows how these regions of drag effects might influence risks and need for more regulations. The figure below plots perigee altitude (since that largely determines drag effects) versus inclination for all rocket bodies in the Satellite Catalog from late 2016; there were 968, many of which are in the three clusters examined in this paper. Spire is clearly in the high drag effect region (green tinting). Iridium and two of the clusters are in the intermediate drag effect zone (yellow tinting) where the primary drag effects will be felt during periods of high solar activity. OneWeb and the last cluster are in the low drag effect region (red tinting) where drag has very little cleansing effects except for the very smallest objects (e.g., less than 1cm).
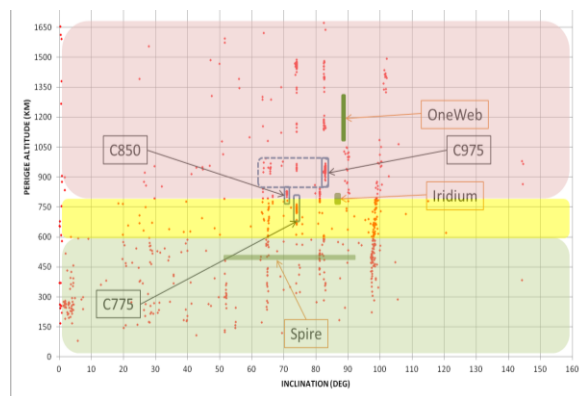

Figure 2. Drag effects provide an important aspect of the space hardware residing in LEO.

It is quite haunting that an event that could double the catalog population has at least a 1/1200 chance of occurring annually (i.e., C850). Any of these inter-cluster collisions would produce significant amounts of debris that would measurably affect satellites within ±100-150km. While OneWeb is largely above the fray from these events, they might be affected by collisions in C975 but Iridium is right in the middle of C775 and just below C850. The figure below shows the three constellations and three clusters plotted on the same ORDEM-derived spatial density curves for LEO.
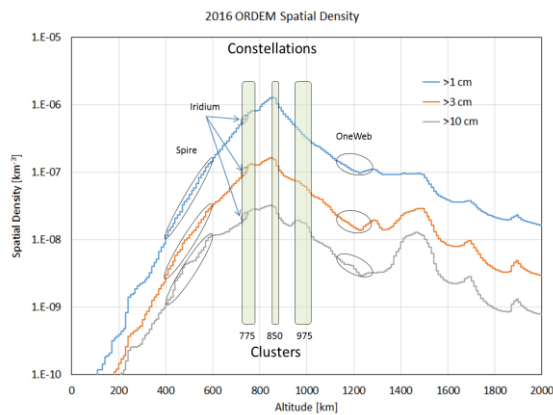

Figure 3. Depicting the cluster locations relative to the constellations shows how there may be a relationship between these two different types of space hardware.

The spatial density plot (number of objects of three size thresholds per volume plotted against altitude) shows that Spire and OneWeb have both selected altitudes for their constellations out of the most debris-populated regions of LEO.

What may not be apparent, but is instructive to state explicitly, is that the clusters of massive derelicts have larger aggregate masses and collision cross-sections than the three constellations yet these derelict objects have no means to detect or maneuver away from collisions like operational satellites. However, there is little attention being taken of these objects.

So, one may ask, with constellation members with individual satellite masses orders of magnitude less than the abandoned rocket bodies and dead payloads in neighboring clusters plus likelihood of inter-constellation collisions near zero, what should the aerospace community be focusing their attention on?

OPERATIONAL RISK

The debris environment places certain operational risks/burdens on operators and they, in turn, place certain operational risks/burdens on each other, including resource expenditures and risks of financial loss. Operationally, close approach analysis and mitigation poses a significant resource burden for maneuverable satellite systems and constellations. In scenarios where no maneuver is undertaken, there is still significant expenditures of labor due to the number of meetings, follow-on analysis and inter- and intra-operator coordination required. In some cases, these activities require an equivalent number of personnel necessary to support launch and early operations. In scenarios where a maneuver is undertaken, fuel is expended and useful life of the satellite asset is potentially cut short.

In contrast, constellations that cannot maneuver are able to avoid much of the effort that comes along with close approach coordination, since their ability to mitigate the threat is based on atmospheric drag which costs nothing in terms of spent propellant and only minor disruptions to their operations. The challenge for future constellations (and those that regulate them) in increasingly crowded orbits is to find a workable set of customs and reliable set of tools that addresses close approach warnings as a routine and expected situation with delegated responsibilities tied to agreed-upon courses of action.

First, there are a number of common misconceptions that will need to be understood for any meaningful traffic management framework to be implemented: (i) all close approaches are the same, (ii) information on close approaches is fairly accurate, and (iii) maneuvers can be executed perfectly and in a timely fashion and, thereby, eliminate the risk of collision.

Misconception 1: All close approaches are the same.

As a community, satellite operators do not do a good job of differentiating and detailing the differences between various potential collisions in terms of probabilities and consequences. A near collision involving two derelict rocket bodies is a completely different scenario from a close approach between two operational satellites, yet they may both be lumped into the same close approach bin. Papers that merely study number of close approaches, we feel miss the point. Specifically, hundreds of 1km close approaches pose much less risk then a single 100m conjunction.

As a satellite operator, all other resident space objects are effectively navigation hazards with variable and inconsistent knowledge of each hazard's state. As illustrated above, the number of derelict vehicles and debris are more than an order of magnitude greater than the number of active operational satellites. Therefore, the odds are that close approaches will occur between an active satellite and components of the debris environment which are not capable of maneuvering (rather than a maneuverable satellite). Thus, space traffic management operator-to-operator procedures, while necessary, may not be relevant in a large majority of close approaches. Overly simple rules as what operators "must" do may not have any practical impact on most close approaches, while having large economic impacts on such operators.

Misconception 2: Information on close approaches is fairly accurate.

Three critical pieces of information regarding a close approach may be wrong or irrelevant.

First, the knowledge of your own satellite's position is usually accurate to less than 100m in LEO. Unfortunately, in most cases a radar-derived position of the owner operator satellite used to compute the close approach will never be as accurate as their own knowledge of their satellite. This may lead the operator to ignore an externally-derived close approach warning.

Secondly and similarly, the knowledge of the conjuncting object's state is important. It may either be static (i.e., from update to update it is unchanging) which leads to questions regarding the currency of the information. Alternatively, it may be highly variable with each update; this may be the result of the object's high area-to-mass ratio or radar tasking inconsistencies.

The third piece of information that results in a tendency to discount the close approach notification is the published covariance matrix for the offending object. The published uncertainty for the other object is often many orders of magnitude greater than the uncertainty for the state knowledge for the owner operator satellite. This lack of certainty in position knowledge may frustrate attempts to determine the best course of action and create discussions within an operator resulting in further analysis and expenses. In these typical cases, where there is a great disparity between the covariance between the two objects, statistics dictate that action is discouraged since the benefits are highly questionable. In some cases, executing a maneuver might be more likely to cause
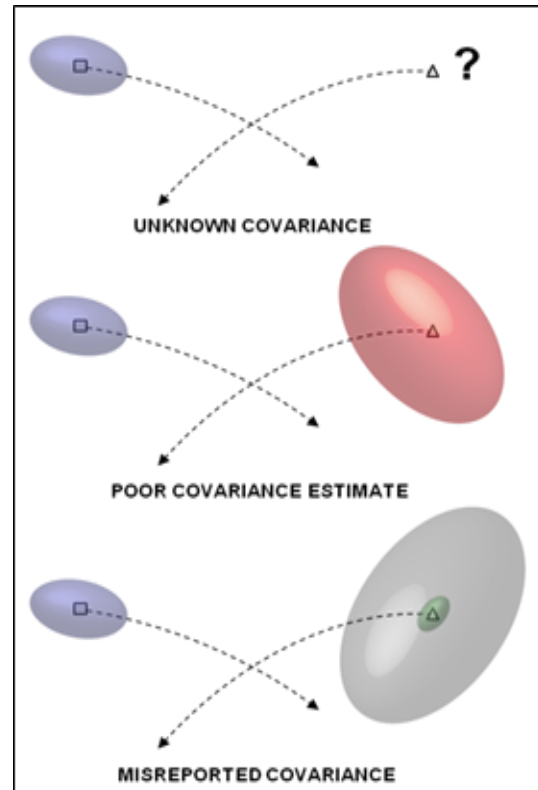

Figure 4. Conjunction characterization is very complicated due to lack of knowledge and natural variability of orbital data.

the collision you are trying to avoid versus just doing nothing.

In fact the risk from information defects and modelling outcomes of maneuvers can be quantified for each of our constellations using the following criteria: (1) object altitude, (2) object status, (3) object attitude, and (4) propulsive capability.

Vehicle altitude is a means to account for the predictability of the orbit and, therefore, the consistency and quality of the resulting trajectory solution. Objects above 800km are not affected significantly by atmospheric drag and are simpler to track and maintain precision orbital solutions, while objects below 600km are significantly perturbed by atmospheric drag and require near persistence monitoring to provide accurate information regarding their trajectory. Resident Space Objects (RSO) between 600 and 800km orbit are in a more benign atmospheric environment with nearly linear decay rates of years and are heavily influenced by solar activity.

The object's status (i.e., either operational or derelict) is a significant aspect in its risk assessment. An

active vehicle with a functioning transponder or Global Positioning System (GPS) receiver will have a more accurate ephemeris than a non-operational vehicle at the same altitude. Again, the number of active satellites is small compared to the debris population, but this factor in and of itself has a large effect on the risk assessment.

The object's attitude (e.g., tumbling, nadir pointing) also plays an important role. Predicting the motion of an inactive tumbling object is challenging below 450km due to the differential drag forces acting on the satellite as opposed to a 3-axis-stabilized satellite with a near constant cross-sectional area exposed to the ram direction. This risk factor is a measure of the solution's stability and ability to provide long-term insight into how the object's trajectory will evolve. When modeling an intact unknown object, a reasonable starting point for its area-to-mass ratio is 0.01 m^2/kg. This ratio holds for 3U CubeSats up to 2,000kg satellites. Many spacecraft have approximately the same area-to-mass ratio due to common space system reliance on solar panels for power generation and the density with which electronics and components can be packed.

The final factor is whether the system has or had a propulsion system. As discussed above, the ability to maneuver is not a panacea for negating the risk of collision. Propulsion systems provide a course of action with additional independent risks that need to be assessed.

This risk assessment approach provides a first order metric regarding the complexity of the encounter, the amount of tracking required and, more importantly, the timeline available to resolve. Using this approach, the most benign object on this scale is a stable low area-to-mass ratio, active satellite above 1100km and the most difficult to model object is an active unstable satellite with propulsion orbiting between 200-450 km. The low LEO active satellite that is unstable, encountering faults and anomalies pose a greater risk to effective maneuvers due to its rapid decay rates and the potential for an off-nominal maneuver. However, this risk is largely offset by the shorter orbital lifetimes of these low-LEO payloads.

Misconception 3: Maneuvers can be executed perfectly and in a timely fashion and, thereby, reduce the risk of collision.

Maneuvers are usually complicated events that require planning, potentially heaters to be warmed, and uploading commands to the vehicle to execute the burn. All of this takes time, and in the case where there is sufficient time, this can be worked out to decrease the probability of collision, but not erase it or the consequences of an impact. In addition, most maneuvers are asynchronous events planned in advance for stationkeeping or orbit maintenance. Even in these benign cases, something may go awry or end up off nominal. Since fuel is usually the critical life-limiting quantity on a satellite, the usual maneuver strategy is to plan for 80% of the correction in the first maneuver with a subsequent maneuver for fine tuning. This conservative approach (from a fuel management perspective) may not be the optimal approach from a collision avoidance perspective.

Given these constraints on the system, the chance that a mostly correct maneuver will avoid an object with a significant uncertainty in its state is a challenging task. However, the advent of electric thrusters provides some extra flexibility and capability in this regard. Additionally, the chance for operator error or a system fault is non-zero and is usually not included in the calculus to select the most prudent course of action. It cannot be overstated that the Cosmos-Iridium collision of 2009 was enabled by a planned and ostensibly safe maneuver. This is especially true for CubeSats; while it may seem logical that CubeSats present less risk to others if they have a propulsive capability (and thus the ability to avoid a collision), many familiar with typical CubeSat operators have posited that giving a novice space operator this added capability might actually backfire from a collision probability perspective.

It is clear that operational risk are burdens imposed by the debris environment on constellations and by constellations on themselves and other operators. In addition, these risks raise complicated issues for space traffic management that simple rules (everyone carry insurance, everyone carry propulsion, etc.) cannot solve. For instance, there is zero chance for Spire to impose a risk of loss on Iridium given the different altitudes they inhabit. However, there is a risk for Iridium to impose a loss on Spire given that it intends to put the Iridium satellites into a disposal orbit that intersects with Spire's. Should Iridium have to buy insurance in favor of Spire? Similarly, OneWeb plans to transit orbits used by Iridium. If an Iridium and OneWeb satellite collide, whose fault is it? Who needs to move in case of a conjunction event? Do these maneuvers require a set of rules ahead of time?

What about debris caused by a satellite's destruction, say Iridium-33, which pollutes the orbits of other operators and necessitates many maneuvers a year? Is

it Iridium's "fault" that a OneWeb satellite is hit by debris from the Iridium-33 collision event when transiting that altitude? Should Iridium's insurance have to cover that eventuality especially given that OneWeb is choosing to transit Iridium's orbits? We do not necessarily have answers to these questions, but believe the complexity involved counsels strongly against overly simplistic and inflexible rules.

NON-ADHERENCE RISK

Non-adherence risk is the risk that an operator cannot or does not comply with rules and regulations in place to minimize debris generation. Currently, this refers to the 25-year de-orbit guideline and minimization of debris directive set out in the IADC Space Debris Mitigation Guidelines (advocated by several international entities) and in various national requirements or customs that derive therefrom. The 25-year de-orbit guideline states that an object passing through LEO should de-orbit within 25 years of mission completion. Adherence to the existing 25-year guideline has been much less than expected as can be seen in Figure 5, inserted below.

We think considering non-adherence risk is relevant, because non-adherence has a large impact on other risks and regulators should consider the risk of non-adherence with any rule or system they adopt. The Traffic Management Study found that CubeSats that are launched into lower LEO orbits (and thereby follow the 25-year guideline) do not significantly raise the risk of collision in LEO. [13] Other studies have found that CubeSats without propulsion systems

launched into high LEO orbits (and thereby violate the 25-year guideline) do significantly raise the amount of debris in LEO over extended periods. [14] Given the comparable area-to-mass ratio of larger satellites, we see no reason why non-adherence to the 25-year guideline is not equally or more concerning for large satellites, especially since by definition they would result in more derelict mass abandoned on orbit.

This non-adherence comes in three basic forms: (i) permitted non-adherence, (ii) technical non-adherence, and (iii) willful non-adherence.

Permitted non-adherence can occur when a jurisdiction does not have any orbital debris rules or allows an operator to obtain a waiver of those rules (either prospectively or retroactively). Given that background guidelines are from the United Nations and IADC, some countries are more committed to meeting them than others. New rules must apply and be enforced internationally in order to prevent the effective arbitraging of regulatory regimes.

Technical non-adherence occurs when a satellite cannot adhere to established rules. For instance, when a given satellite is deployed in a dead on arrival state or when a given satellite is disabled by background debris, as described previously or otherwise fails on orbit.

Willful non-adherence occurs when an operator violates the orbital debris mitigation requirements to which it is subject in a voluntary way, in other words,
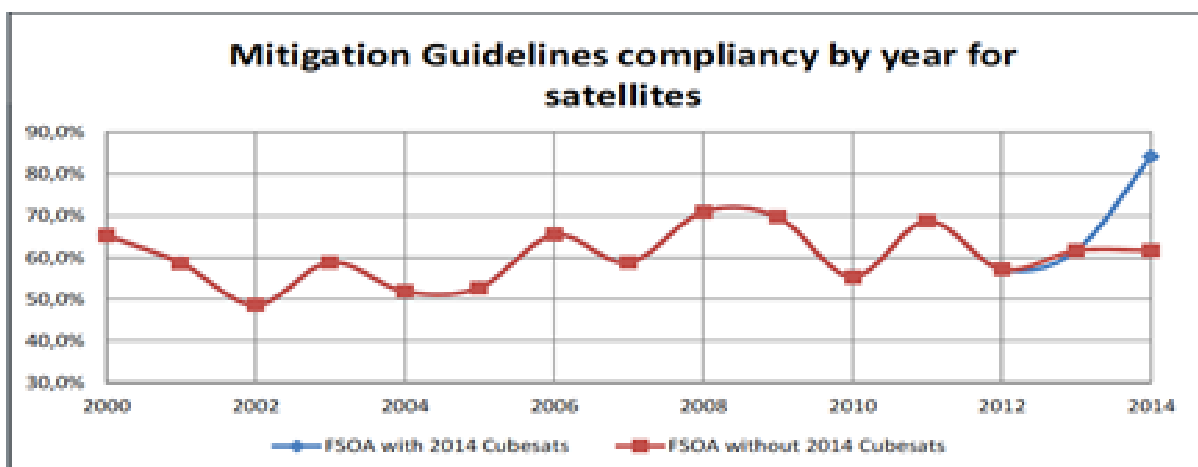

Figure 5. Debris mitigation compliance has not been very good over the last 15 years. Source: Journée de Synthèse Débris, Review of Mitigation Rules Compliance in LEO (2000-2014) (June 9, 2015). FSOA is the French Space Operations Act.

is able to comply but does not. This might occur when end of life maneuvers do not result in an orbit that meets the 25-year guideline or such maneuvers are not performed before such time as fuel is inadequate to complete them. Given that it is impossible to distinguish between willful and technical non-adherence without evidence available only from the operator or following a government investigation, we are making no claims or implications in this paper that anyone has willfully violated the 25-year guideline or their orbital debris mitigation plans. However, we do note, as a general matter, that there is a huge economic incentive to keep a high value asset operating as long as possible in orbit and that systems fail in unexpected ways and at unexpected times leading to at least technical non-adherence in many cases.

We now examine all three of our constellations through the lens of "non-adherence risk".

Iridium is the only constellation examined with an operational track record which can be evaluated. While Iridium was launched before the 25-year guideline was implemented (in fact its constellation is subject to much more stringent requirements), Iridium has asked the FCC for the newer less stringent 25-year guideline to apply. This is an example of permitted non-adherence (a waiver of stricter existing requirements), although the FCC should be commended for only waiving in part the

more stringent rules to which Iridium was originally subject. [16]

In terms of technical non-adherence, Iridium inhabits an altitude where a satellite dead on arrival, disabled by background debris, and/or running out of fuel will not de-orbit for 200 years. In addition, Iridium satellites must continue to function and preserve enough fuel to complete their end of life maneuvers. In fact, their plan states specifically that "satellite disposal is predicated on the end-of-life satellite retaining sufficient functionality to accomplish the disposal maneuver sequence." [15] Therefore, technical non-adherence risk is high for Iridium.

This is shown by actual experience as documented in Figure 6 below which plots operational altitudes of Iridium satellites over time. This chart shows that at least two of Iridium satellites have failed to execute on their deorbit plans out of 11 end-of-life satellites by 2015 (or 19% non-compliance). [17] Still this record is better than the average compliance as shown in Figure 5, at least so far.

Turning to OneWeb, there is no history of permitted non-adherence, as OneWeb has not asked for any exemptions from the 25-year guideline. In fact, OneWeb's disposal plan appears to be far better than the 25-year guideline. In addition, OneWeb's deployment plan has satellites deploying at 500 km, where they would still meet the 25-year guideline in a
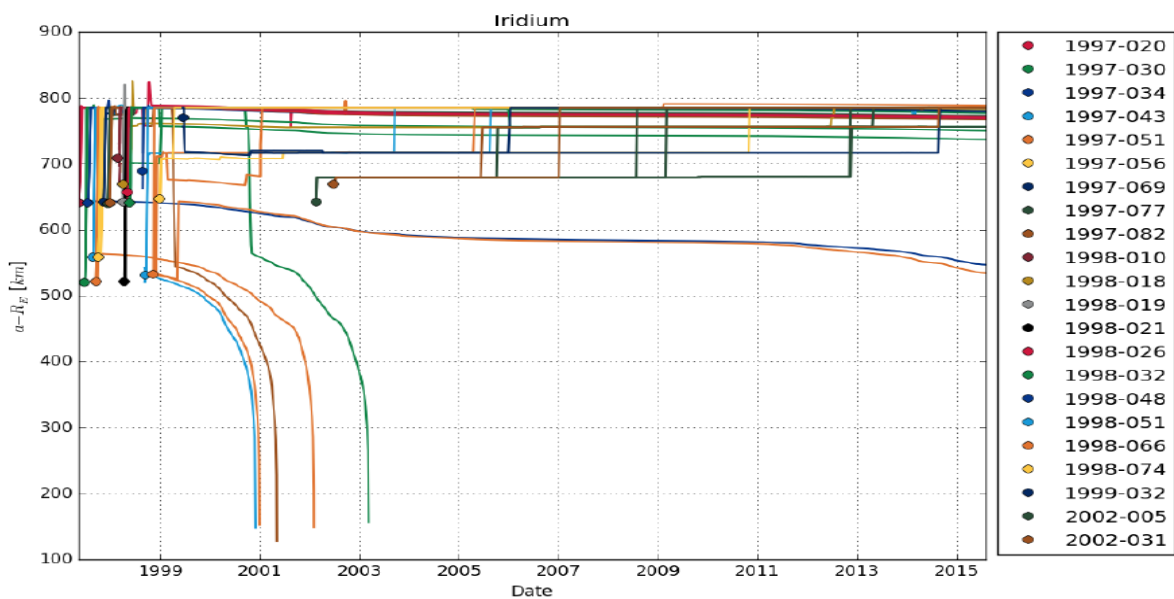

Figure 6. Iridium's track history of deorbiting old satellites is better than the industry average and may improve as they respond to the next generation satellites being deployed to upgrade their constellation.

dead on arrival scenario, which mitigates technical non-adherence risk in the deployment phase. However, there remains the possibility of a OneWeb satellite being disabled at its operational altitude and thus not de-orbiting for hundreds of years. As discussed previously, there is also risk inherent in OneWeb's transit through LEO which should be carefully weighed against the risk of a dead on arrival satellite at OneWeb's operational orbit. This risk can best be mitigated by higher reliability systems.

Spire's LEMUR-2 constellation is purposefully deployed into altitudes that will meet the 25-year guideline under a worst case dead on arrival scenario. [18] Spire is relying on physics to meet the guideline.

While popular consensus is that CubeSats are largely non-compliant to debris mitigation guidelines, Figure 5 actually noted the large increase in compliance with the 25-year guideline in 2014 when CubeSats were first considered. Compliance jumped from 60% to over 80% when CubeSats were considered. Given that compliance was in the range of 50-70% before CubeSats, sensational news stories that 1 in 5 CubeSats violates the 25-year guidelines (20%) actually demonstrates a higher level of compliance than the baseline for other satellites. [19] Still, we believe this is not sufficient.

We do not mean to argue that the 25-year guideline is the answer in and of itself. In fact, we will discuss shortly why such an overly simplistic rule makes less sense for such a complicated problem like orbital debris. We merely hope to highlight that risk of non-adherence to whatever set of rules and regulations is eventually adopted has a meaningful impact on the debris environment. This risk, can of course, be mitigated by technical or physical controls that are designed to meet the requirement on a consistent and high fidelity basis. However, it seems clear that "voluntary" compliance has not been successful to date in guaranteeing a high level of compliance from any one type of system.

SUMMARY

With this paper we hope to have highlighted a few key considerations with respect to the orbital debris environment. First, the debris environment in low earth orbit is highly complex. Different orbits have different physics characteristics (spatial density, atmospheric drag, perturbations, etc.) that are critical to any risk analysis. Second, satellite operators have different characteristics that drive the risk their satellites pose and face from the debris environment, including different deployment and disposal plans

and different satellite bus characteristics. These complexities require well thought out rules based on physics. It is likely that a "one size fits all orbits" or a "one size fits all operators" rule or rules "will no doubt create economic consequences, while potentially *not* mitigating safety risks significantly." [20]

Next, the risk a collision poses to the orbital environment is probability times consequence, not just probability. In addition, risk is certainly not number of satellites or close approaches. Let's be more precise and start measuring collision risk in a meaningful way. We should also keep the risks posed by and to economically useful constellations in perspective. At 775km, 850km, and 975km there are concentration points where the background environment is on the precipice of debris-generating events that will exacerbate an already tenuous situation in LEO. One collision within the C850 cluster will create 16,000 trackable fragments while one collision between two CubeSats will create 14 trackable fragments. As much (if not even more) time and effort should be spent on solving the issue of massive derelicts as regulating constellations.

In addition, given the true state of affairs when it comes to the complexity of close approach avoidance, coordination among constellation operators is necessary. It is proposed that close coordination between operators is a far more efficient and effective means of collision avoidance than rigid rules and customs imposed by a "celestial arbitrator." Close approaches in low earth orbit are not a simple highway (or even air traffic) management problem. Orbital collision avoidance will require a highly complex series of mutually interdependent actions based on an imperfect understanding of initial states and executed from hundreds to thousands of kilometers away. We posit that the ability to maneuver is an added dimension that requires proper assessment from timelines to execution success versus a panacea for mitigating all potential collisions.

Next, assuming the world can come up with a set of rules or guidelines that will ensure that orbital debris does not get out of control, regulators should create workable mechanisms to ensure compliance by their operators.

Finally, LEO has limited volume and, as such, debris generation needs to be managed carefully. However, while current debris mitigation guidelines (and even the debate over debris remediation efforts) rest on the impetus to prevent a long-term cascading effect of

orbital collisions (i.e., the Kessler Syndrome), rules and frameworks should focus on current and near term space flight safety. The orbital debris environment does not have to be preserved now for the next 200 years, it needs to be preserved now for the next 10-20 years and then rules and frameworks need to be adapted to the new facts and circumstances that exist at that later date.

REFERENCES

[1] *See* Pub.L. 114-90, November 25, 2015, Section 109, Paragraph c(7).

[2] *See* Traffic Management Study at 8.

[3] Committee on the Peaceful Uses of Outer Space, Scientific and Technical Subcommittee, Fifty-fourth session, Vienna, Guidelines for the long-term sustainability of outer space activities, October 18, 2016.

[4] *See* Traffic Management Study at 16.

[5] *See* Legal Narrative to WorldVu Satellites Limited, Petition for Declaratory Ruling Granting Access to the U.S. Market for the OneWeb System, File No. SAT-LOI-20160428-00041 at page 7.

[6] *See* Traffic Management Study at F-1 (stating after 2013, 3U CubeSats became the most frequent type of launched spacecraft in the 1-50kg range).

[7] *See* Traffic Management Study at F-1 (stating after 2013, 3U CubeSats became the most frequent type of launched spacecraft in the 1-50kg range).

[8] *See* SpaceWorks Microsatellite Forecast at 3.

[9] *See* Exhibit A to Application for Minor Modification Before the FCC, SAT-MOD-20080701-00140 at page A-3 (the "Iridium Orbital Debris Modification Request"); *See also*, Order and Authorization of the FCC, DA 14-1118 at page 4 (July 31, 2014) approving in part Iridium's request to modify its Orbital Debris Plan to allow for up to 10 satellites to be placed into an orbit that would take up to 25 years to decay and deferring Iridium's request for such a de-orbit plan for the remainder of the Iridium fleet ("FCC Iridium Debris Order").

[10] *See* OneWeb Orbital Debris Mitigation Plan attached to Letter from Jennifer Hindin, Counsel for WorldVu Satellites Limited, Wiley Rein LLP, to Marlene H. Dortch, Secretary, Federal Communications Commission, IBFS File No. SAT-LOI- 20160428-00041, Call Sign S2963 (filed Nov. 10, 2016) at page 4.

[11] McKnight, D.S. et al, "Proposed Series of Orbital Debris Remediation Activities", 7th European Conference on Space Debris, Darmstadt, April 2017.

[12] Don Kessler provided this warning in the keynote address to the 7th European Conference on Space Debris held in Darmstadt, Germany in April 2017.

[13] *See* Traffic Management Study at F-3.

[14] *See* Peterson, Glenn E., et al., Effect Of CubeSats On Collissions And Long-Term Debris Growth In Near-Earth Environment, Presented to the 67th International Astronautical Congress, IAC-16, A6,7,8,x32388 at page 7.

[15] *See* Iridium Orbital Debris Modification Request at A-3.

[16] *See* Iridium Orbital Debris Modification Request and FCC Iridium Debris Order.

[17] European Space Agency, Future Large Constellations in LEO and the Space Debris Environment – A Technical Analysis at Slide 9 (the "ESA Technical Analysis").

[18] *See* SAT-AMD-20161114-00107, Exhibit B: Spire Global, Inc. Orbital Debris Risk Mitigation Plan at 1-2, filed November 14, 2016.

[19] *See* Space News, 1 in 5 CubeSats violates International Orbit Disposal Guidelines at http://spacenews.com/1-in-5-cubesats-violate-international-orbit-disposal-guidelines/ (last visited June 30, 2017).

[20] *See* Traffic Management Study at 16.

APPENDIX A. Technical Description of the Poisson Distribution Applied to Orbital Debris Encounters

In order to test the hypothesis that the Poisson probability is an underestimation, empirical encounter rates (ER) were calculated at various miss distances (from 500m-5km in 500m intervals) and compared to a Poisson distribution. The empirical ERs were calculated from JSpOC data gathered from May 2015-May 2016 and encounter statistics created by Integrity Applications Incorporated (IAI) for this same timeframe. These were then compared to the ER found using equations (1-4) where Λ is the frequency within the Poisson probability density function (i.e., P(k)) taken from the kinetic theory of gases analogy.

$$\lambda = AC * VR * SPD \quad (1)$$

where

$SPD = \frac{N}{Vol} = spatial\ density,\ \#/km^3$
$N = number\ of\ derelicts,$
$Vol = volume\ swept\ out\ by\ cluster,\ km^3$
$AC = collision\ cross\ section,\ km^2$
$VR = relative\ velocity,\ km/s$

$$P(k) = \frac{\lambda^k e^{-\lambda}}{k!} \quad (2)$$

where

$\lambda = expected\ number\ of\ occurrences\ over\ time,\ t$
$k = number\ of\ occurrences\ (k = 0,1...)$

When it is assumed that there will be very few events, the probability of that rare event can be determined by 1 (i.e., the total all possible occurrences) minus the probability of no events. The result is represented by the well-known expression in equation (3).

$$P(1) = 1 - e^{-\lambda t} \quad (3)$$

The PC is the collision hazard to one satellite from N objects in the population. When we are looking at PC we are only concerned about the target, e.g., operational satellite getting hit by cataloged debris. Conversely, when we have a cluster of massive derelicts we are concerned about collisions between any two of the N objects in the cluster.

This is called the collision rate (CR) and is the cumulative PC for N objects on each other.

CR is represented by:

$$CR = \sum_1^N PC = \left(\frac{1}{2}\right) N\ (AC * VR * SPD * T)\ (4)\ [1]$$
$$= (N^2/2) * (AC * VR * T) / (Vol)$$

When the encounter dimension is considered to be half of the miss distance then the collision rate is equivalent to the encounter rate (ER).

The next logical question is "if we accept the probability found with a Poisson distribution, when might the first collision occur?" Using a gamma distribution this can be evaluated for a given confidence level in equation (5).

$$\Gamma = -ln(1 - C) * \left(\frac{1}{CR}\right) \quad (5)$$

where Γ is the number of years until the first event
C is the confidence interval
CR is Poisson-derived encounter rate

The table to the right shows the number of years for the first Poisson event predicted by the gamma distribution at different confidence levels for a CR of 1/3045. Please note that we have already shown that the Poisson distribution may underestimate the actual physical encounter rate so these may overestimate the time until the first collision event. Using the empirically-derived collision rate of 1/2500, the first Poisson event would occur within 25yrs with a 1% confidence. Note that the SL-16 cluster has been intact since 2007, so the "clock started ticking ten years ago."

Confidence	Years Before First Event
1%	31
5%	156
10%	321
25%	876
50%	2110
75%	4221
90%	7011

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[1] Note that the ½ term appears to insure that we do not double count possible encounters within the cluster.