INFLUENCE OF ORBITAL DEBRIS ON SPACE ARCHITECTURE EFFICACY

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ABSTRACT

This study examines how orbital debris may affect the efficacy of space architectures over the next decade. Parametrical modeling in two dimensions is performed to examine sensitivities related to space architectures under the influence of the growing space debris hazard. The two dimensions include (1) three debris environment scenarios and (2) three low Earth orbit (LEO) space architecture options. Results highlight the possibility that spaceflight safety can be enhanced by anticipating and leveraging space system design trends and knowledge of debris hazard evolution uncertainties. There is neither a sure fire way to prevent debris from impacting LEO constellations but also no certainty that current practices will lead to failures over the next decade. However, actions taken now will have long-lasting impact on future deployments and operations.

BACKGROUND

Orbital debris and satellite constellations are both "trending" in the aerospace community. Satellite constellations of smallsats have great potential for responsive global capability for communications, remote sensing, internet delivery, surveillance, reconnaissance, and on and on. Similarly, the pallor of orbital debris hangs over many space systems creating angst about the potential for mission-degrading impacts and even complete destruction. Catastrophic collision events will produce hundreds to thousands of fragments and pose collision risks to even more operational satellites. While constellations are typically expert at avoiding collisions with their own systems they will be threatened by debris from other activities.

The figure to the right (provided by Mark Matney at NASA) plots the spatial density (SPD) of orbital debris of various sizes in low Earth orbit (LEO). This data shows how the debris hazard peaks near 850km in altitude (in the heart of the sun-synchronous orbits) plus another little peak around 1500km. The 10cm curve represents what is cataloged and, therefore, whose encounters can be predicted. A collision with a 10cm fragment would most likely breakup any operational satellite it might strike. Unfortunately, fragments as small as 1cm cannot be seen reliably but can degrade or

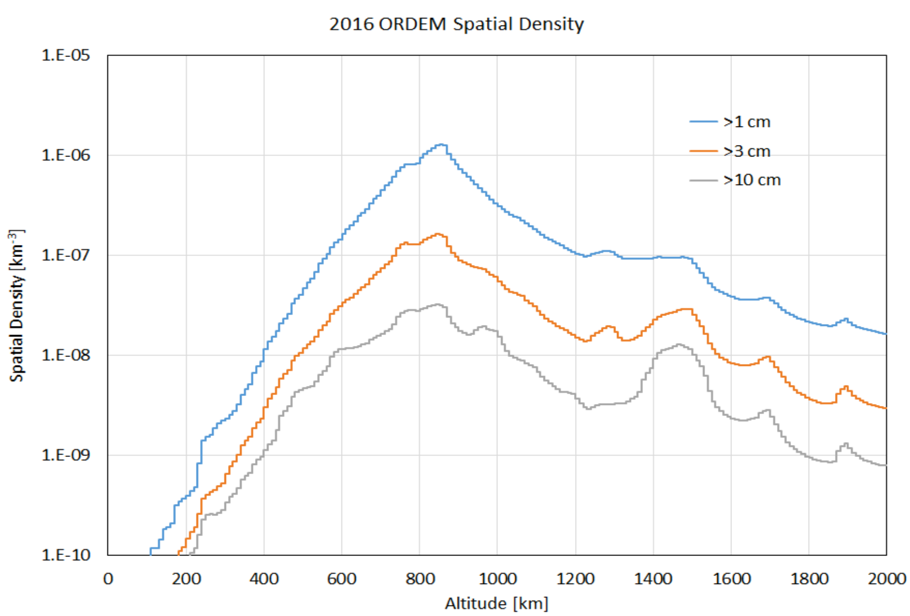

Figure 1. The spatial density (number of objects per km^3) plot provides a description of lethal collision hazard. Unfortunately, we can only track the objects larger than 10cm in LEO.

terminate the mission of an operational satellite. This 1-10cm range of debris is often called the lethal nontrackable (LNT) population. Constellations may be considered more at risk since they may have many satellites and, thus, a large total exposed area to the debris hazard. Collisions with any debris, 1cm or larger, will likely render the impacted satellite nonoperational, yet only a small amount of that lethal population can be seen and avoided.

It should be noted that ORDEM has recently been updated and the new model is being continually scrutinized and modified, as appropriate, so the data that created Figure 1 represents the design environment to which NASA space systems must use to design satellites currently under development.

ANALYSIS

This paper will examine how collision events might corrupt the space environment sufficiently in and around satellite constellations to impair their viable operation due to impacts from debris. The timeframe of the analysis is 2016-2026 assuming no significant debris hazard increase except for the breakup events modeled in order to isolate the tradeoffs between the breakup events and constellation designs. The calculations will not consider direct interaction of the debris with the constellations as a debris source. Only breakups of existing derelicts on orbit (i.e., depleted rocket bodies and defunct payloads) will be considered. Three typical (but hypothetical) constellations will be used as the baseline:

1. RED: 200 satellites at 800km, 65° inclination, and collision cross-section of 2m^2.
2. WHITE: 20 satellites at 1000km, 108° inclination, and collision cross-section of 10m^2.
3. BLUE: 1000 satellites at 1200km, 85° inclination, and collision cross-section of 4m^2.

For each constellation, it is assumed that there will be no collisions amongst themselves and no spares on orbit. As a baseline, the (a) current probability of collision (PC)/year and (b) cumulative PC for ten years at current levels will be calculated for an individual satellite and the entire constellation from debris populations with the lower size thresholds of 1cm and 10cm.

The table below summarizes this baseline scenario assessment.

BASELINE SCENARIO (1/10cm)							
Const.	Description	Exposed Area Const.	SPD (#/km^3)	PC/yr/Sat	PC/10yrs/ Sat	PC/yr/ Const.	PC/10yrs/ Const.
RED	50x2m^2@800km/65°	100m^2	9E-7/3E-8	9E-4/2E-5	6E-3/2E-4	3%/9E-4	30%/0.9%
WHITE	20x8m^2@1000km/108°	160m^2	3E-7/2E-8	8E-4/5E-5	8E-3/5E-4	2%/0.1%	10%/1%
BLUE	600x4m^2@1200km/85°	2400m^2	1E-7/4E-9	1E-4/5E-6	0.1%/5E-5	8%/0.3%	50%/3%

Table 1. Baseline constellation collision hazard shows that high number of satellites in the Blue constellation offsets the lower spatial density at 1200km altitude.

The LNT (i.e., 1cm population) SPD is about 15-30 times larger than the cataloged (i.e., 10cm population) SPD. The PC/yr for individual satellites in our three constellations peaks for the Red constellation as it is near the peak SPD but the White constellation is only slightly smaller. However, the Blue constellation, deployed at 1200km, surpasses both Red and White constellations' PC/yr/constellation (i.e., considering the total cross-sectional area of a constellation) even though it is in a less debris-populated region due to its large total exposed area.

In an absolute sense, there is a 10-50% chance that at least one of each of the constellation members will be struck by a 1cm fragment (or larger). This would likely terminate that satellite's mission and might even liberate debris that would pose additional hazards. The probability of any one member of each of the constellations being struck by a 10cm or larger object over ten years is between 0.9-3%. An encounter between an object of this size with any of the spacecraft would almost undoubtedly result in a complete fragmentation event and the creation of hundreds of additional debris fragments.

While the SPD values for the existing debris populations varied by a factor of from 8-9x across the three constellations, the cumulative PC over the ten years for each of the constellations only vary by less than a factor of 5x. If the Blue and White constellations had switched altitude locations, this would not have been the case; the large exposed area of the Blue constellation largely made up for being placed at a lightly debris-populated altitude.

The inclination of the constellations have not been used directly in these calculations but they do have two secondary influences on hazard assessments. First, the retrograde orbit of the White constellation will yield a higher impact velocity on average; it will probably be closer to 12km/s versus the typical 10km/s for LEO. Both velocities will result in hypervelocity impact events but the larger impact velocity will have a bit more kinetic energy available for a given impactor size since the kinetic energy term uses the square of the impact velocity. Secondly, the likely latitude of a collision will be between 5-20° below the maximum latitude (i.e., inclination for a direct orbit) so the inclinations partially drive where events might occur latitudinally.

The second phase of the analysis introduces small breakups (i.e., 2,000 10cm fragments and 30,000 1cm fragments over a 450km altitude span) at the following altitudes and times: 800km in 2017, 1000km in 2019, 900km in 2021, and 800km in 2023. The breakup fragments were generated by the rule of 1 trackable and 15 LNT per kg of mass involved based on past collision events. [1] In addition, the debris populated volume shells above and below a breakup altitude symmetrically. 20% of the debris is contained in 50km (±25km) centered on the breakup altitude; 50% of the debris is contained in 150km centered on the breakup altitude, 70% of the debris is contained in 250km centered on the breakup altitude, and finally, 90% of the debris is contained within 450km centered on the breakup altitude.

The table below provides the new results for the five small breakup events scenario.

FIVE SMALL BREAKUPS SCENARIO (1/10cm)							
Const.	Description	SPD ($\#/km^3$) Start	**SPD ($\#/km^3$) END**	**PC/yr/Sat END**	**PC/10yrs/ Sat**	**PC/yr/ Const. END**	**PC/10yrs/ Const.**
RED	$50x2m^2$@800km/65° Total area of $100m^2$	9E-7/3E-8	**1E-6/6E-8**	**9E-4/4E-5**	**0.9%/4E-4**	**4%/0.2%**	**40%/2%**
WHITE	$20x8m^2$@1000km/108° Total area of $160m^2$	3E-7/2E-8	**7E-7/4E-8**	**2E-3/1E-4**	**0.2%/0.1%**	**3%/0.2%**	**30%/2%**
BLUE	$600x4m^2$@1200km/85° Total area of $2400m^2$	1E-7/4E-9	**1E-7/7E-9**	**2E-4/8E-6**	**0.2%/8E-5**	**10%/0.5%**	**70%/5%**

Table 2. The sequence of five small breakups shows that the lower two constellations were affected much more by this sequence of breakups which makes sense as the breakups occurred where most of the mass already resides (i.e., between 800-1000km).

The cumulative PC from the cataloged for all constellations over 2016-2026 increased, however, as the probability gets very large for a single event it is difficult to push it closer to one. The White constellation had the greatest increase relative to the baseline due to being affected by all breakups to some extent. Conversely, the BLUE constellation was only affected by the 1000km altitude breakup.

The LNT hazard increased from 10-50% (baseline scenario) to 30-70% (for four small breakups). Due to the altitude of the breakups, the SPD nearly doubled for the Red and White constellations. The larger number of satellites in the Blue constellation, however, more than made up for the lower PC/yr/sat to have the maximum cumulative PC for both LNT and cataloged debris.

The last scenario assumes two large collisions between massive derelict rocket bodies: two SL-8s collide in 2017 at 950km (likelihood/yr ≥ 1/200) and two SL-16s collide in 2020 at 850km (likelihood/yr ≥ 1/4000). The SL-8 collision would produce approximately 2,850 cataloged objects and 42,750 LNT; slightly larger than the "small" breakup events in the last scenario. However, the SL-16 collision is likely to produce about 16,600 cataloged objects and 249,000 LNT. While these events are less likely than the smaller collisions run in the first scenario, the fact that they are clustered their PC values may be underestimated; there is ongoing research to quantify this potential difference. [1,2]

TWO LARGE BREAKUPS SCENARIO(1/10cm)							
Const.	Description	SPD (#/km^3) Start	**SPD (#/km^3) END**	**PC/yr/Sat END**	**PC/10yrs/ Sat**	**PC/yr/ Const. END**	**PC/10yrs/ Const.**
RED	50x2m^2@800km/65° Total area of 100m^2	9E-7/3E-8	**2E-6/1E-7**	**0.1%/9E-5**	**1%/6E-4**	**7%/0.4%**	**50%/3%**
WHITE	20x8m^2@1000km/108° Total area of 160m^2	3E-7/2E-8	**1E-6/7E-8**	**0.3%/2E-4**	**2%/2E-3**	**5%/0.4%**	**40%/3%**
BLUE	600x4m^2@1200km/85° Total area of 2400m^2	1E-7/4E-9	**1E-7/4E-9**	**1E-4/5E-6**	**0.1%/6E-5**	**8%/0.3%**	**60%/3%**

Table 3. The sequence of two large breakups contributed more to the debris hazard than four small events; a SL-16 collision in essence would double theLEO cataloged population in one instance but not spread it throughout LEO.

Even though we had a larger number of fragments being introduced by these two large breakup events, the 1200km constellation remain unscathed due to its location relative to these events. Again, this reinforces the constellation altitude selection criteria of "go where others have not been" being a credible approach. The Red and White constellations did not fair so well. It should be noted that the effects of both breakups were somewhat tempered by the fact that the events did not occur at the same altitudes as the constellations. When a breakup occurs it literally throws about half of the debris to higher orbits but making the breakup altitude the perigee of these fragments. In the same way, half of the objects are spread to lower altitudes with the apogee of each being the breakup altitude. Therefore, if you are either well above or below the breakup altitude (say 10s of kms) your system immediately avoids half of the debris liberated, whereas if the breakup occurs at the same altitude as your system, all of the debris can potentially strike your system later. This is why a breakup within a monolithic constellation can be so devastating.

The figure to the right shows the PC values the cataloged population for the three constellations as a function of time for the "two large breakups" scenario. It is clear that the second event, the SL-16-on-SL-16 event, contributed the most to the deterioration of the survivability of the Red and White constellations. This is not a surprise as the mass involved in an SL-16 collision is about 25 times the mass involved in the Chinese Feng-Yun event of 2007 which generated over 3,000 trackable fragments.

However, if the SL-16 event was offset to be at the same altitude of any of the constellations, the LNT cumulative PC values would have

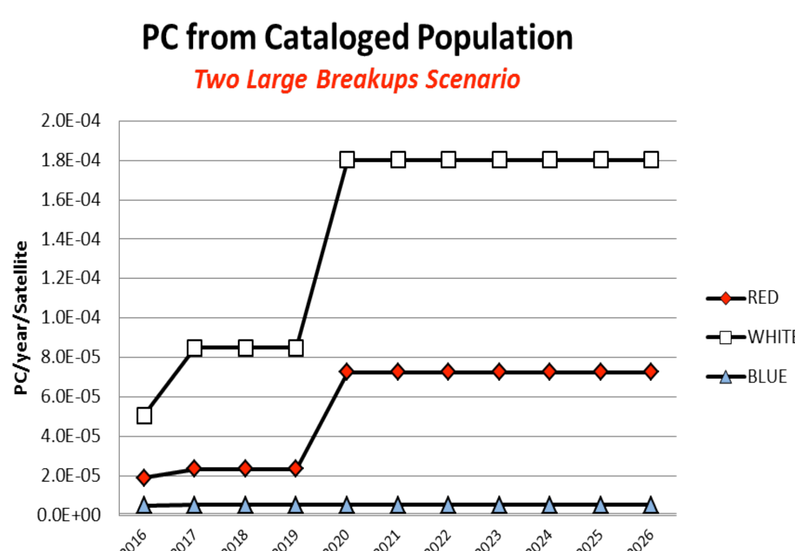

Figure 2. The probability of collison increased most significantly after the SL-16 collision at 850km in 2020.

approached 80-90%.

Table 4 provides a direct comparison between the two breakup scenarios examined. In both cases, the Blue constellation avoided much of the debris produced due to its higher altitude. Similarly, the effects on the Red and White constellations were tempered by it not happening at the exact altitude of either one.

Comparing End SPD by Scenario (1/10cm)				
Const.	Description	SPD (#/km^3) Start	**SPD (#/km^3) END**	
			4 Small Breakups	**2 Large Breakups**
RED	50x2m^2@800km/65° Total area of 100m^2	9E-7/3E-8	**1E-6/6E-8**	**2E-6/1E-7**
WHITE	20x8m^2@1000km/108° Total area of 160m^2	3E-7/2E-8	**7E-7/4E-8**	**1E-6/7E-8**
BLUE	600x4m^2@1200km/85° Total area of 2400m^2	1E-7/4E-9	**1E-7/7E-9**	**1E-7/4E-9**

Table 4. The end spatial density provides a depiction of the deterioration of the debris environment at each constellation altitude showing how the Blue constellation is affected the least from the breakups modeled.

The population at the Red and White constellation altitudes as much as tripled but this did not include the inevitable other events that might produce debris such as abandoned payloads and rocket bodies; explosion events; and mission-related debris releases. These types of events have, however, reduced significantly over the last twenty years as debris mitigation guidelines have been followed more and more. [3]

CONCLUSIONS

This analysis highlights the criticality of preventing massive-on-massive collisions in LEO. Several smaller (i.e., typical of previous collision) occurring sooner did not influence the hypothetical constellations as much as a single SL-16 collision. This should motivate the community to monitor and characterize clusters of massive derelicts in LEO of which an SL-16 event would be the most consequential. In addition, this reinforces the need for the community to put a higher priority on debris remediation systems development and operations.

The results of this study also show the benefit of diversification in constellation architectures. Diversification, in this application, means avoiding monolithic constellations: spread satellites across multiple altitudes and have different types/sizes of spacecraft. Placing satellites at a variety of orbital altitudes provides a hedge against a single breakup corrupting a specific altitude swath affecting all of the satellites within a constellation.

REFERENCES

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