CONSEQUENCES OF LEO SATELLITE COLLISIONS – THE FRAGMENTS

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ABSTRACT

This paper addresses the consequences when two large-constellation satellites collide catastrophically. Monte Carlo simulations based on the NASA Breakup Model and Blitzer decay model are used. Starlink, OneWeb, and Lightspeed satellites are considered, and compared to CubeSats in the same orbits.

Smaller, less massive, satellites in lower orbits may be the key to sustainable LEO constellations. Collisions between smaller satellites, such as CubeSats, have significantly less consequence than collisions between more massive satellites – there are fewer fragments. Also, collisions at lower orbits have less consequence – the fragments decay sooner. Both factors can contribute to more robust LEO sustainability.

1. INTRODUCTION

Significant work has been reported in the literature on estimating the probability of collisions between low Earth orbit (LEO) satellites, see [1] and [2]. The reality of large constellations with thousands, and even tens of thousands, of satellites in LEO increases the probability of catastrophic intra-system collisions occurring. This paper addresses the consequences of such collisions.

Satellites that cannot maneuverer, cannot avoid collisions. Loss of maneuverability can result from sub-systems failures in the maneuverer chain or from collision with small objects that disable these subsystems. Every time a satellite is not maneuvered in response to a low probability conjunction warning, there is a non-zero collision risk. Additionally, every time a satellite is maneuvered, there is another non-zero probability that the maneuver will result in a collision. In both cases, with enough conjunctions occurring, even six sigma events can become likely.

On 10 February 2009, the 689-kg Iridium 33 satellite collided with the 900-kg COMOS 2251 satellite approximately 800-km above Siberia [3]. Twelve years later, the consequence of that collision is 1,433 trackable debris objects with apogees up to 1,650-km, plus a likely much larger number of lethal non-trackable (LNT) debris objects and those that are non-lethal but can still degrade satellite performance.

What can be expected when two large-constellation satellites collide catastrophically? What are the distributions and lifetimes of the fragment clouds? How do these distributions change as a function of the mass of the colliding satellites? How will these debris clouds impact LEO sustainability?

These questions are addressed using Monte Carlo simulations based on the NASA Breakup Model and Blitzer decay model. Orbital parameter and area-to-mass ratio distributions are used to characterize the initial fragment clouds. These distributions are propagated over time using drag models to determine trajectories and orbital lifetimes.

A particularly relevant case, that of equal-mass satellites colliding at the intra-system crossing points of large-constellations is used to illustrate the results. Several cases based on actual large constellation's parameters are explored. It is shown that even collisions occurring in the so called "clean out zone", below 600-km, can have decades long consequences across a large swath of LEO altitudes. It is also shown that the consequences of collisions decrease dramatically with the masses of the satellites involved.

2. LARGE CONSTELLATIONS

Actual orbital and mass parameters [4] for the Starlink (SpaceX) and OneWeb systems are used. Specification sheet [5] parameters are used for the Lightspeed (Telesat) system. Mass data is not readily available for other large constellations. The collision consequences of intra-system collisions for each constellation are compared to those of 12U CubeSats. Sensitivity to collision altitude and to satellite mass are also evaluated.

The key parameters are summarized in Table 1. For systems with planes at multiple altitudes and inclinations, the parameters from one of the most populous orbits are chosen. The mass of the 12U CubeSat is modeled using the typical 1.333 kg/U mass limit.

Table 1. Constellation Parameters

System	#Sats	Altitude	Inc	Mass
Starlink	4,408	550 km	53°	260 kg
OneWeb	648	1,200 km	87.9°	148 kg
Lightspeed	298	1,325 km	50.9°	700 kg
CubeSat	–	-	-	16 kg

3. MODELS

The fragmentation and decay models are described in Sections 3.1 and 3.2, respectively.

3.1. Fragmentation Model

The MASTER-8 version of the EVOLVE 4.0 NASA Standard Breakup Model for spacecraft [6] is used. The number of fragments is determined from a power law distribution characterized by the object masses and the minimum fragment size.

The number of fragments with size greater than d_{MIN} (m) is

$$N = 0.1(m_S + m_P)^{0.75} d_{MIN}^{-1.71} \quad (1)$$

Figure 1 shows the number of lethal fragments (>10 cm) as a function of satellite mass for intra-system collisions of equal mass satellites.

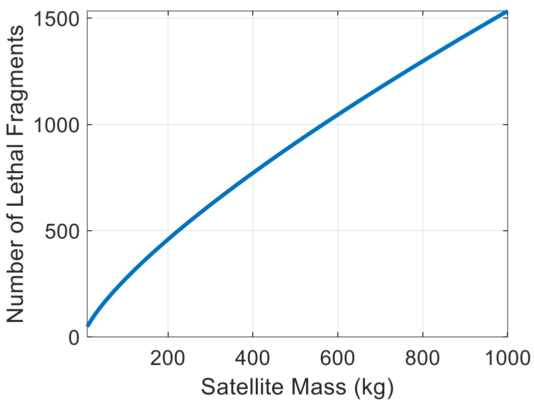

Figure 1. Number of Lethal Fragments (>10 cm) v. Satellite Masses for Equal Mass Collisions

Assuming that all collisions are fragmenting (specific kinetic energy of projectile, $\frac{m_P v_I^2}{2m_S}$, greater than 40 J/kg) and truncating the minimum fragment size to d_{MIN}, the cdf for fragment diameter is

$$cdf(d_F) = \frac{d_F^{-1.71}}{d_{MIN}^{-1.71}} \quad (2)$$

Which has solution

$$d_F = p^{-0.585} d_{MIN} \quad (3)$$

The fragment diameter probability distribution is shown in Figure 2 for $d_{MIN} = 0.1\ m$.

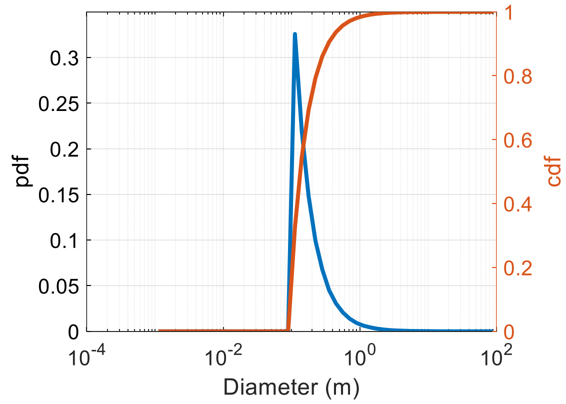

Figure 2. Diameter Distribution (d_{MIN} = 0.1 m)

A bi-normal distribution for $\chi = log_{10}(A/M_F)$ parametrized on $\delta = log_{10}(d_F)$ is used to characterize the area-to-mass ratio

$$\rho(\chi, \delta) = \alpha \frac{1}{\sigma_1\sqrt{2\pi}} e^{-(\chi-\mu_1)^2/(2\sigma_1)} + (1-\alpha)\frac{1}{\sigma_2\sqrt{2\pi}} e^{-(\chi-\mu_2)^2/(2\sigma_2)} \quad (4)$$

where the parameters α, μ_1, μ_2, σ_1, and σ_2 are functions of δ.

This distribution does not have a closed form solution and must be solved numerically. Figure 3 shows the fragment area-to-mass probability distribution.

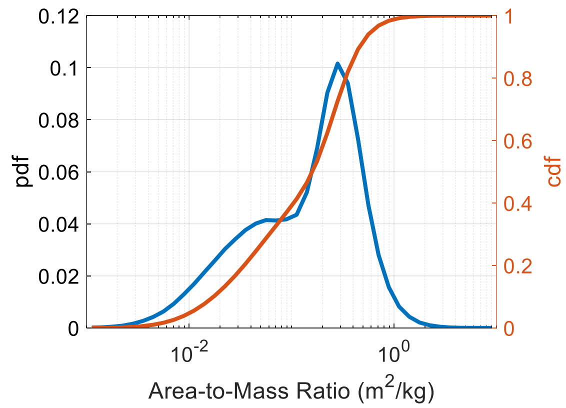

Figure 3. Area-to-Mass Distribution

The fragment delta velocity (m/s) is related to the fragment A/M (m²/kg) for fragmenting collisions by

$$cdf(v) = \frac{1}{2}\left(erf\left(\frac{v - 0.2\chi - 1.85}{0.4\sqrt{2}}\right) + 1\right) \quad (5)$$

Which has solution

$$\Delta v_F = 10^{0.2\log_{10}((A/M)_F)+1.85+0.4\sqrt{2}\mathrm{erf}^{-1}(2p-1)} \quad (6)$$

This distribution is show in Figure 4.

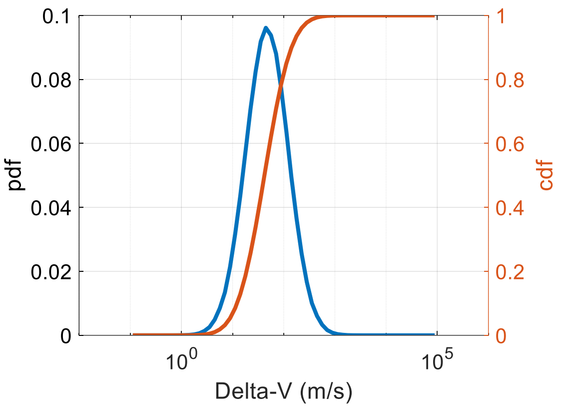

Figure 4. Delta-V Distribution

The orbital elements for each fragment are obtained by uniformly distributing the delta-V vector over a sphere and adding it to the fragment state vector. Fragments with perigee less than 200-km are assumed to have reentered. Figure 5 and Figure 6 are the distributions of fragment mean altitudes and inclinations, respectively, relative to those of the colliding satellites.

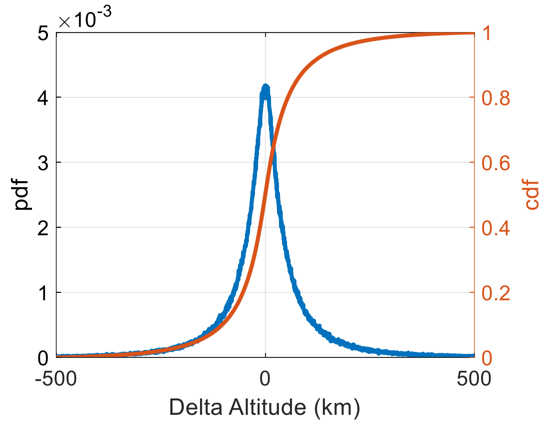

Figure 5. Distribution of Fragment Mean Altitude Relative to Collision Altitude

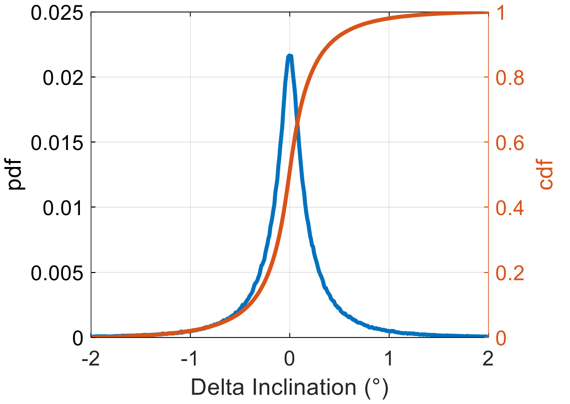

Figure 6. Distribution of Fragment Inclination Relative to Inclination of Colliding Object

3.2. Decay Model

Following [7], the changes in semi-major axis (a), eccentricity (e), inclination (i), right ascension of ascending node (Ω), and argument of perigee (ω) over one revolution due to drag are

$$\Delta a = -2\pi\delta a^2 \rho \left(I_0 + 2eI_1 + \frac{3e^2}{4}(I_0 + I_2) + \frac{e^3}{4}(3I_1 + I_3) \right) \exp(-c) \tag{7}$$

$$\Delta e = -2\pi\delta a\rho \left(I_1 + \frac{e}{2}(I_0 + I_2) - \frac{e^2}{8}(5I_1 - I_3) - \frac{e^3}{16}(5I_0 + 4I_2 - I_4) \right) \exp(-c) \tag{8}$$

$$\Delta i = -\frac{\pi a \omega_\oplus \delta\rho}{2\eta\sqrt{Q}} \sin i \,(I_0 - 2eI_1 + (I_2 - 2eI_1)\cos(2\omega)) \exp(-c) \tag{9}$$

$$\Delta\Omega = -\frac{\pi a \omega_\oplus \delta\rho}{2\eta\sqrt{Q}} (I_2 - 2eI_1) \sin(2\omega) \exp(-c) \tag{10}$$

$$\Delta\omega = -\Delta\Omega \cos i \tag{11}$$

where

$$c = \frac{ae}{H} \tag{12}$$

$$\delta = Q\frac{A}{m}C_D \tag{13}$$

$$Q = 1 - \frac{2\omega_\oplus (1-e)^{3/2} \cos i}{\eta\sqrt{1+e}} \tag{14}$$

$\omega_\oplus$ is the Earth's rotation rate (rad/s)
H is the scale height (km)
η is the mean motion (rad/s)
C_D is the drag coefficient

$\frac{A}{m}$ is the area-to-mass ratio (m^2/kg)
ρ is the atmospheric density at perigee (kg/m^3)
I_s is the output of the modified Bessel function of the first kind of order S with input c (Eq. 12).

The DAS solar flux (F10.7) table [8] is used to model solar cycle variations of the atmospheric density.

4. SIMULATION RESULTS

The 2009 Iridium-COSMOS collision is used to validate the models. Figure 7 is a Gabbard diagram of the trackable (typically >10 cm) fragments from that collision reported by Space-Track [9] in 2021. The simulated result is shown in Figure 8. The similar shapes and total number of objects suggest that the simulation is providing reasonable results and may be slightly underestimating the number of fragments.

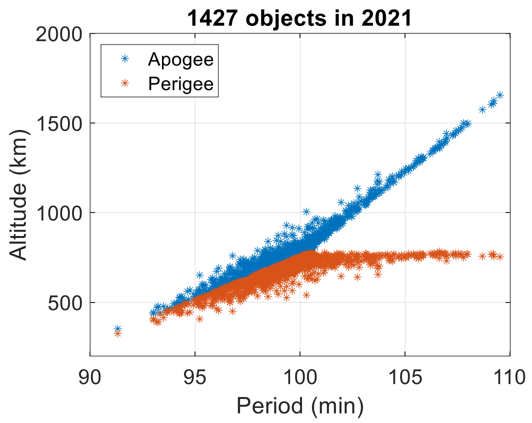

Figure 7. Iridium-COSMOS Debris (Space-Track)

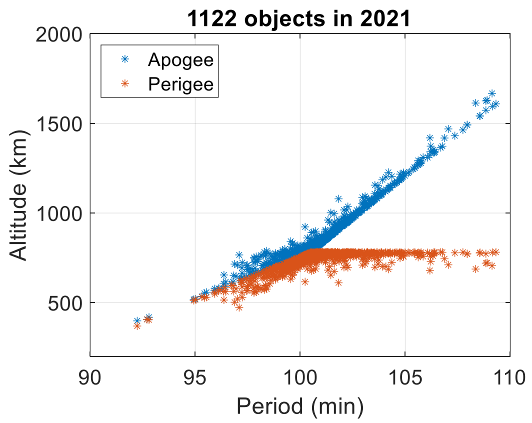

Figure 8. Iridium-COSMOS Debris (Simulated)

Gabbard diagrams are provided for hypothetical 2022 collisions of Starlink (Section 4.1), OneWeb (Section 4.2), and Lightspeed (Section 4.3) satellites. The situation 25 years later is also shown. For each constellation, the results are compared to those of a hypothetical 2022 collision of 12U CubeSats in the same orbits as the original satellites. Section 4.4 examines the sensitivity to collision altitude and satellite mass.

4.1. Starlink

The spread of lethal fragments from a hypothetical Starlink satellite collision with another Starlink satellite in 2022 is shown in Figure 9. Even though the collision occurs at 550-km, the fragment apogees extend to over 1500-km.

Figure 10 shows the spread 25 years later. In this collision, 11 of the original 530 lethal fragments remain in orbit. On average, 56 lethal fragments remain in orbit after 10 years, and 9 after 25 years.

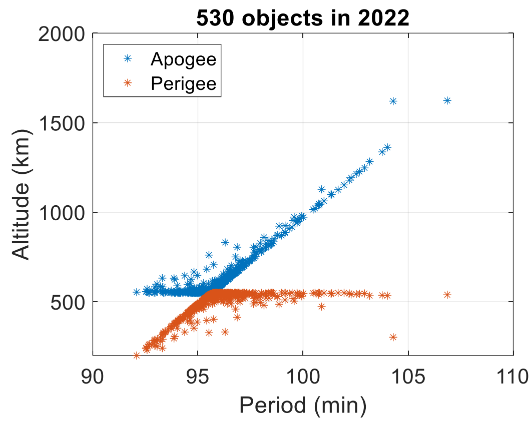

Figure 9. Fragments from Hypothetical 2022 Starlink-Starlink Collision at 550 km

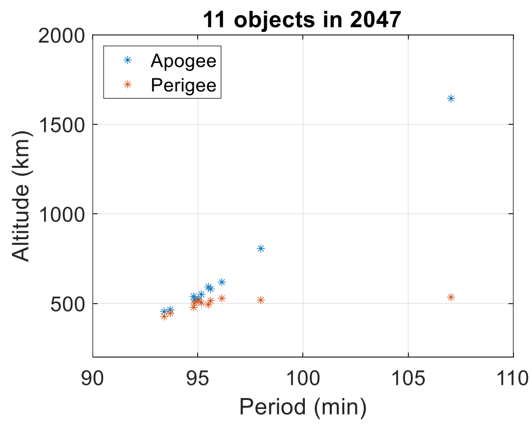

Figure 10. Fragments from Hypothetical Starlink-Starlink Collision at 550 km – 25 Years Later

Figure 11 and Figure 12 are fragments from a hypothetical 2022 collision of two 12U CubeSats in the Starlink 550-km orbit, immediately following the collision and 25 years later, respectively. The initial number of fragments, 60, is almost an order of magnitude less than for the Starlink collision, and all fragments have reentered within 25 years. On average, 6 fragments remained in orbit after 10 years, and 1 after 25 years.

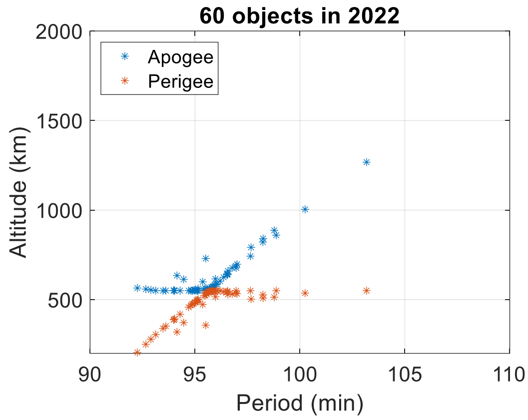

Figure 11. Fragments from Hypothetical 2022 CubeSat-CubeSat Collision at 550 km

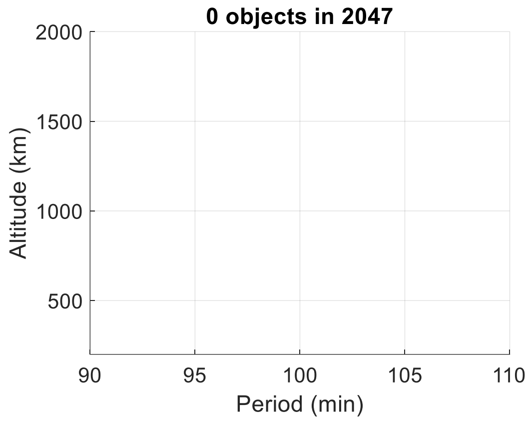

Figure 12. Fragments from Hypothetical CubeSat-CubeSat Collision at 550 km – 25 Years Later

Figure 13 compares the average number of fragments from hypothetical 2022 collisions of two Starlink satellites and of two CubeSats. The lower mass CubeSat collisions have significantly less impact.

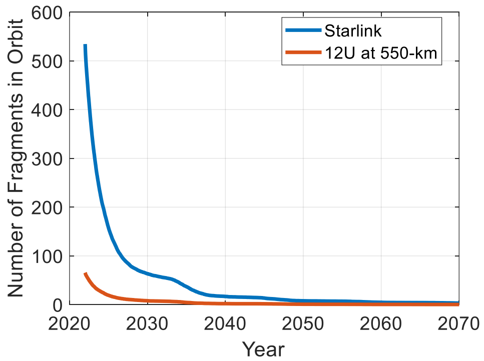

Figure 13. Average Number of Starlink and 12U CubeSat Fragments from 2022 Collisions at 550-km

4.2. OneWeb

Figure 14 shows the spread of lethal fragments from a hypothetical 2022 collision of two OneWeb satellites. Figure 15 shows the spread 25 years later. In this collision, 358 of the original 364 lethal fragments remain in orbit.

Even though the OneWeb satellites are less massive than the Starlink satellites, the higher collision altitude results in greater impact. The fragments extend over a larger swath of LEO, in this collision from 500 km to 2,000 km, and they persist in orbit for centuries.

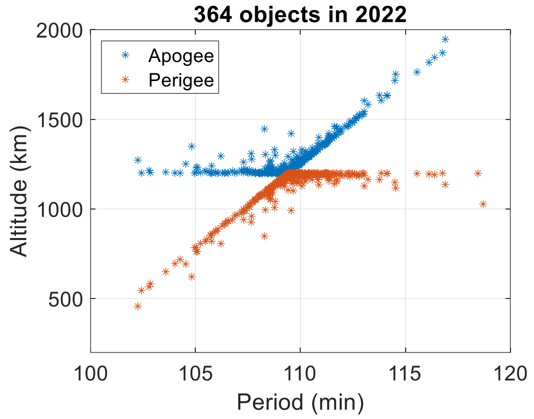

Figure 14. Fragments from Hypothetical 2022 OneWeb-OneWeb Collision at 1,200 km

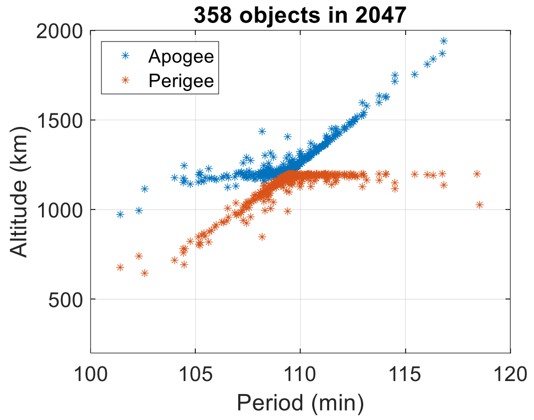

Figure 15. Fragments from Hypothetical OneWeb-OneWeb Collision at 1,200 km – 25 Years Later

Replacing the OneWeb satellites with CubeSats reduces the number of fragments by a factor of five, see Figure 16 and Figure 17, However, with the collision occurring at 1,200-km, even CubeSat fragments persist for centuries.

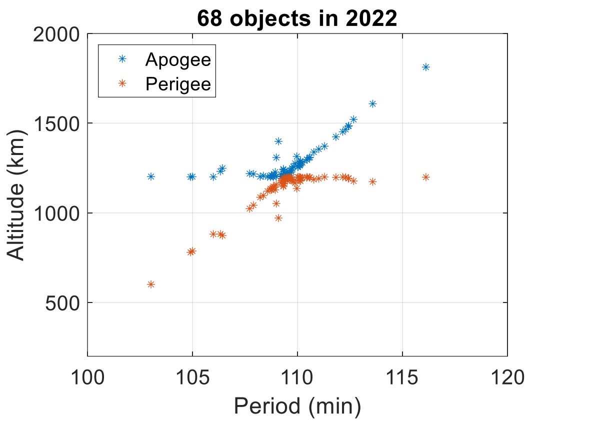

Figure 16. Fragments from Hypothetical 2022 CubeSat-CubeSat Collision at 1,200 km

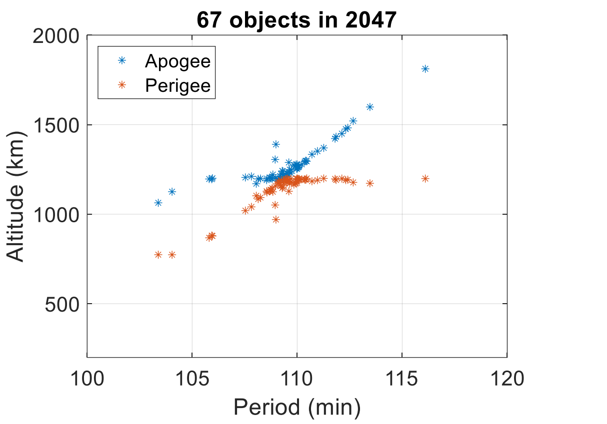

Figure 17. Fragments from Hypothetical 2022 CubeSat-CubeSat Collision at 1,200 km – 25 Years Later

Figure 18 shows the average number of fragments as a function of time for hypothetical 2022 collisions of two OneWeb satellites and of two CubeSats. Collisions in the 1,200-km orbit are more consequential than those in the 550-km orbit – fragments persist for centuries.

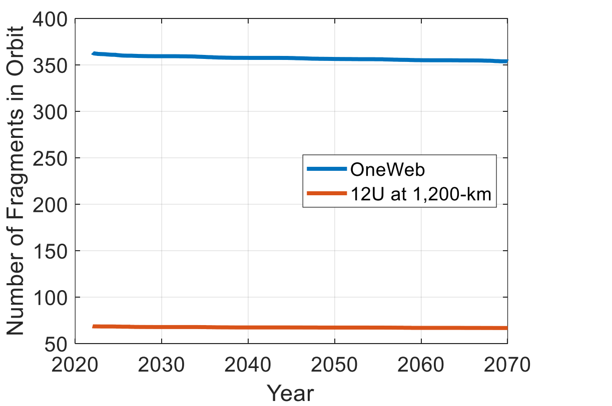

Figure 18. Average Number of OneWeb and 12U CubeSat Fragments from 2022 Collisions at 1,200-km

4.3. Lightspeed

The spread of lethal fragments from a hypothetical Lightspeed satellite collision with another Lightspeed satellite in 2022 is shown in Figure 19. The fragments are spread across LEO, from 200-km to 2,000-km. Figure 20 shows the spread 25 years later. In this collision, 1,160 of the original 1,168 lethal fragments remain in orbit.

The combination of more massive satellites (700 kg) and higher altitude (1,325-km) means that a Lightspeed collision will have greater consequences than either a Starlink or a OneWeb collision, with over 1,000 fragments persisting across LEO for centuries.

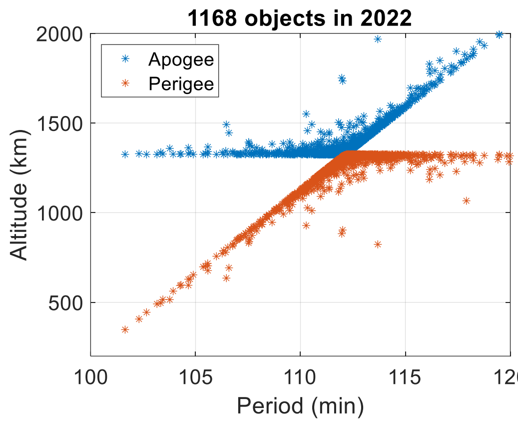

Figure 19. Fragments from Hypothetical Lightspeed-Lightspeed Collision at 1,325-km

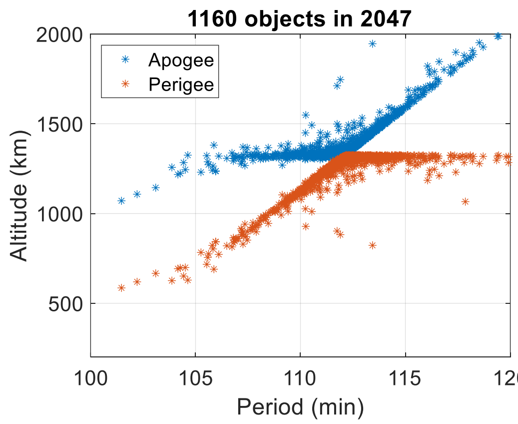

Figure 20. Fragments from Hypothetical Lightspeed-Lightspeed Collision at 1,325-km – 25 Years Later

Figure 21 and Figure 22 show an example of fragments from a hypothetical 2022 collision of two 12U CubeSats in the Lightspeed 1,325-km orbit, immediately following the collision and 25 years later, respectively. The initial number of fragments, 69, is a factor of seventeen less than for the Lightspeed collision, however, 68 remain in orbit after 25 years.

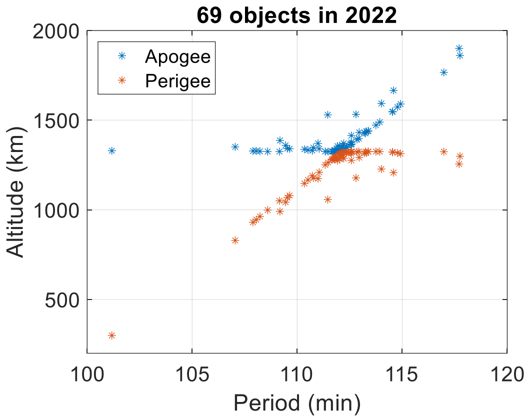

Figure 21. Fragments from Hypothetical 2022 CubeSat-CubeSat Collision at 1,325 km

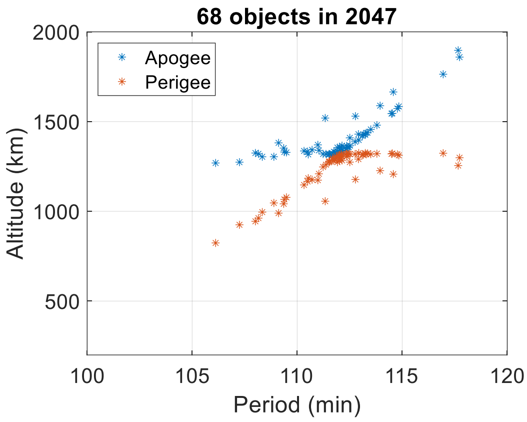

Figure 22. Fragments from Hypothetical 2022 CubeSat-CubeSat Collision at 1,325 km – 25 Years Later

The average number of fragments over time for hypothetical 2022 collisions of two Lightspeed satellites and of two CubeSats are shown in Figure 23. The massive Lightspeed satellites result in over ten times as many fragments as the CubeSat collisions. Fragments from collisions at 1,325-km can remain in orbit for centuries, regardless of satellite mass.

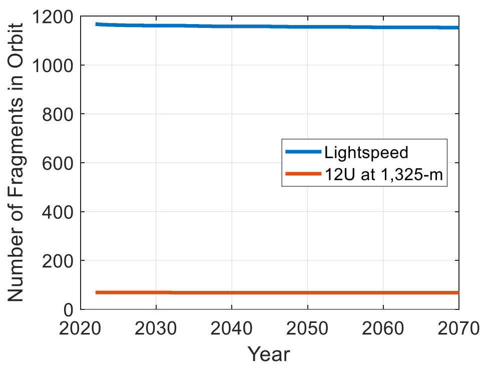

Figure 23. Average Number of Lightspeed and 12U CubeSat Fragments from 2022 Collisions at 1,325-km

4.4. Altitude and Mass Sensitivity

To access the sensitivity to collision altitude, CubeSat-CubeSat collisions are simulated at altitudes from 300-km to 600-km. The results are shown in Table 2. For each altitude, the number of years post collision required for all fragments to have deorbited is provided at the 50%, 90%, 95%, and 99% confidence levels.

Table 2. Years Post Collision at Which All CubeSat Fragments Have Deorbited

Altitude	Confidence			
(km)	50%	90%	95%	99%
300	0.3	0.9	1.2	2.3
350	1.1	2.7	3.5	6.4
400	2.7	6.4	15.0	17.6
450	6.8	16.7	24.6	55.9
500	15.5	42.9	60.1	>100
550	37.0	99.7	>100	>100
600	79.6	>100	>100	>100

Even with CubeSats, collisions at altitudes above 500 km can have centuries of consequence. Collisions above 600 km have a >10% probability of impacting LEO for over 100 years.

Table 3 shows the sensitivity to satellite mass for collisions of satellites in a 450-km, 45° inclination orbit. Masses of 16 kg (12U CubeSat), 148 kg (OneWeb), 260 kg (Starlink), and 700 kg (Lightspeed) are considered. For each mass, the number of years post collision required for all fragments to have deorbited is shown at the 50%, 90%, 95%, and 99% confidence levels.

Table 3. Years Post 450-km Collision at Which All Fragments Have Deorbited

Mass	Confidence			
(kg)	50%	90%	95%	99%
16	6.7	16.4	24.4	47.5
148	15.2	36.2	49.0	>100
260	19.5	45.4	58.1	>100
700	25.5	56.7	74.6	>100

At their original orbit altitudes, fragments from collisions within the Starlink, OneWeb, and Lightspeed constellations persist in orbit for over 100 years over 10% of the time. Operating these satellites at 450-km reduces this to <5%.

5. CONCLUSION

Smaller, less massive, satellites in lower orbits may be the key to sustainable LEO constellations. Collisions between smaller satellites, such as CubeSats, have significantly less consequence than collisions between more massive satellites – there are fewer lethal fragments. Collisions at lower orbits also have less consequence – the fragments decay sooner. Both factors can contribute to more robust LEO sustainability.

Global and national policies that incentivize operators to deploy less massive satellites (for example CubeSats) and to deploy them at lower orbital altitudes may have the greatest impact on long term LEO sustainability. These incentives must be aligned with the minimum masses and altitudes required to support mission capabilities.

This paper is focused on assessing the immediate consequence of collisions between two satellites in the same constellation. It does not consider the overall impact on sustainability. Studies addressing sustainability are available in [10] and [11],

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