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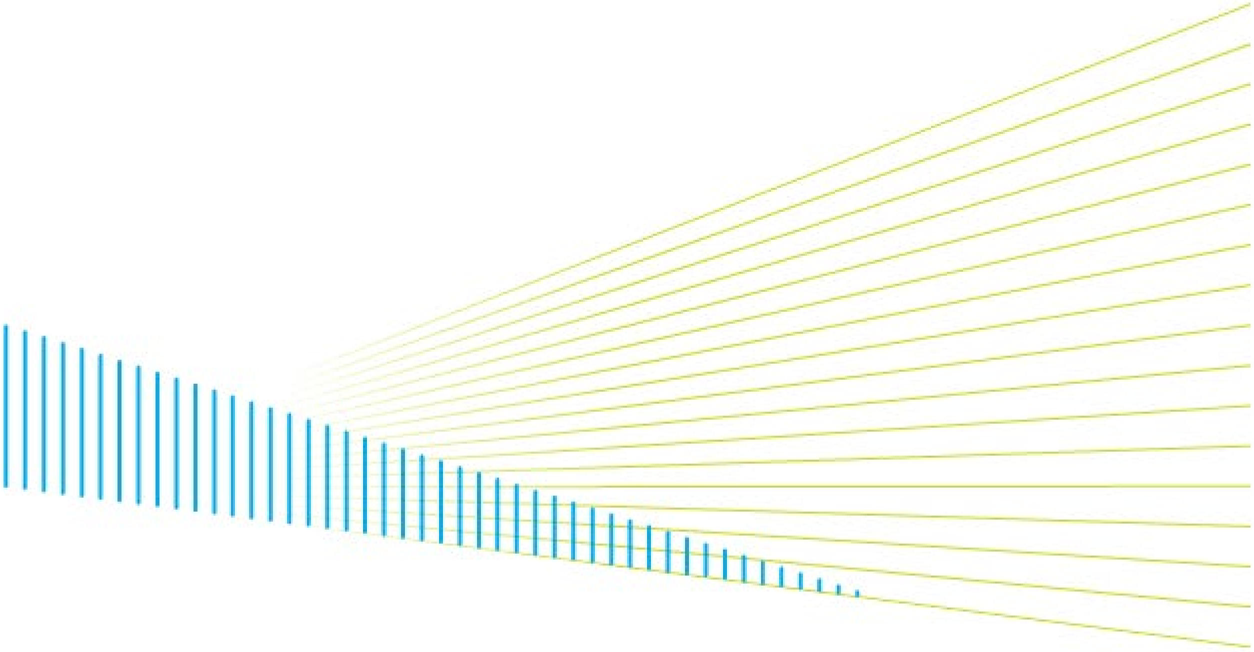
Managing Mega-Constellation Risks in LEO



Viasat

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Executive Summary

A popular conception is: “Space is big. Really big. You just won't believe how vastly, hugely, mind-bogglingly big it is.”[1] However, the part of space near Earth that can be used for human activities is a finite resource, fragile and at risk of over-exploitation, just like resources on Earth. This is particularly true now that the cost of launch has dropped precipitously. Economies of scale that enable small, inexpensive payloads are driving investment in economically expendable spacecraft, and the established norms that drove safe flight for decades are being shattered.

With exponential growth of both space debris and the size of satellite constellations in Low Earth Orbit (LEO), it is increasingly clear that the available “real estate” will not be big enough to support safe and sustainable operation of an unlimited number of satellites.

Because of this, astrophysicists, astronomers, scientists, think tanks, legislators, politicians, and regulators alike are expressing concern about growing orbital congestion in LEO and unduly risky behavior:

> “We are making as much of a mess of the space surrounding our planet as we are of the planet itself.”[2]

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[1] D. Adams, *The Hitchhiker's Guide to the Galaxy* (New York: Harmony Books, 1979), at 73.

[2] H.E. S. Bint Yousif Al Amiri, Minister of State for Advanced Technology, U.A.E., https://www.economist.com/the-world-ahead/2020/11/17/easier-access-to-space-imposes-new-environmental-responsibilities-on-humanity.

> "It's a race to the bottom in terms of getting as much stuff up there as possible to claim orbital real estate."[3]
>
> "The grabbing-up of all the good territory is a reasonable complaint."[4]
>
> "[T]he rise of mega-constellations in low Earth orbit poses the risk of denying access to LEO and radio spectrum by making it impossible for late arrivals to operate there safely and sustainably. It should concern us all and it's time to do something about it."[5]
>
> "When we launch dozens of satellites every few weeks, we remove the environment's ability to inform us of the unintended consequences of our actions and we cannot predict what the dynamic equilibrium state actually is."[6]
>
> "As the Earth orbital environment is getting increasingly congested, concerns about its long-term sustainability, potential overexploitation, and risk of interference are becoming increasingly clear and shared among policymakers, industry leaders, and academia."[7]
>
> "We now stand at a crossroads: if we do not find ways to manage space traffic, our past and *present space activities will jeopardise the safety, security and sustainability of outer space* and, as a result, our future ability to rely on space as enabler of key services in benefit of humankind."[8]
>
> "[S]ignificant domestic and international changes to the use of near-Earth space are urgently needed to preserve access to, and the future utility of, the valuable natural resources of space and our shared skies."[9]

These experts are talking about (i) loss of safe access to LEO, (ii) monopolization of orbital resources by a few actors, (iii) harm to the night sky, the Earth's atmosphere, and the human environment, and (iv) the resulting threat to the continued safe and reliable

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[3] Dr. M. K. Jah, Associate Professor, Department of Aerospace Engineering and Engineering Mechanics, University of Texas at Austin, https://www.wsj.com/articles/elon-musks-satellite-internet-project-is-too-risky-rivals-say-11618827368?mod=searchresults_pos1&page=1.

[4] Dr. J. McDowell, Harvard-Smithsonian Center for Astrophysics, https://www.theverge.com/2021/1/27/22251127/elon-musk-bezos-amazon-billionaires-satellites-space.

[5] M. Alotaibi, Deputy Governor for Radio Spectrum, Saudi Communications and Information Technology Commission (CITC), https://www.spaceintelreport.com/saudi-regulator-itu-must-address-leo-crowding-debris-and-sustainability-before-the-orbit-is-rendered-unusable/.

[6] A. Lawrence, M. L. Rawls, M. Jah, A. Boley, F. Di Vruno, S. Garrington, M. Kramer, S. Lawler, J. Lowenthal, J. McDowell, and M. McCaughrean, The case for space environmentalism, NATURE ASTRONOMY (Apr. 22, 2022), https://www.nature.com/articles/s41550-022-01655-6.

[7] European Space Policy Institute, *Space Environment Capacity: Policy, regulatory, and diplomatic perspectives on threshold-based models for space safety and sustainability* (Apr. 11, 2022), at 39, https://www.espi.or.at/reports/space-environment-capacity/.

[8] European Commission, Joint Communication to the European Parliament and the Council: An EU Approach for Space Traffic Management; An EU Contribution Addressing a Global Challenge (JOIN (2022) 4 final), at 1, https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52022JC0004&from=EN.

[9] J. C. Barentine, et. al., Reimagining Near-Earth Space Policy in a Post-COVID World, Virginia Policy Review, Vol. XV, Issue 1 (Spring 2022), at 59, https://issuu.com/virginiapolicyreview/docs/virginia_policy_review_volume_xv_issue_i.

operation, and future innovative deployment, of space systems around the world. This includes space systems on which consumers, commercial enterprises, scientific research, and defense alike rely—including those that provide vital communications, Positioning, Navigation, Timing (PNT), and Earth observation data and services.

The concerns of these leading voices reflect the reality that limits exist on what types of, and how many, satellites sustainably can occupy LEO.

The unprecedented recent populating of LEO is leading to congestion that significantly increases the risk of collisions, which can have wide-ranging and longstanding impacts on access to space by everyone, including in orbits far above and below the points of collisions. Notably, collision risk is created by more than non-maneuverable satellites. It is an aggregate risk that scales with constellation size and is driven by factors such as (i) the mass and cross-sectional area of the satellites in the system (including considering the effects of changes to the initial design over time), and (ii) the expected number of conjunctions (*i.e.,* "close calls") with operating satellites, derelict satellites, and other orbital debris over the orbital lifetime of each satellite in the system and at each orbit it occupies from launch to reentry into the Earth's atmosphere.

Notably, the number of trackable and untrackable space debris objects is large and continues to grow. So does the number of predicted conjunction events. This means that even a single low probability event can become very likely to occur when one evaluates the entirety of a LEO system, and the aggregate of all space objects it encounters, over the lifetime of that LEO system.

This growing congestion also affects which LEO orbits can be used by other nations to operate their satellites and the terms under which those orbits can be shared.

When the cost of accessing space was high, self-interest motivated exacting standards of care because of the commensurate cost of failure. The term "space-qualified" once meant the industry's highest standards for quality and reliability even in the harsh conditions of space. Those high costs and risks once fostered a safe ecosystem, because the number of objects in space was limited, and the tools to manage them were adequate.

With economic barriers gone, self-interest and the public good are quickly diverging. As the United States Federal Communications Commission (FCC) has recognized, the new approach adopted by some operators has the potential to create significant negative externalities because the costs of an operator's unsustainable and unsafe operations are not borne entirely—or even mostly—by that operator.[10] Rather, those costs are borne by all who use, or benefit from the use of, space. Consequently, certain individual operators are

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[10] *See, e.g., Mitigation of Orbital Debris in the New Space Age,* Notice of Proposed Rulemaking and Order on Reconsideration, 33 FCC Rcd 11352 (2018), at ¶ 89, https://www.fcc.gov/document/fcc-launches-review-rules-mitigate-orbital-space-debris-0 ("Debris generation by on-orbit activities is a negative externality, and is one which could lead to the degradation of the commons of the Earth orbital environment.").

incentivized to prioritize their own short-term interests above the long-term interests in the use of space by all[11]—a true Tragedy of the Commons.

Given the powerful economic incentives at work, we simply cannot rely on voluntary "best practices" or guidelines (whether created at the national or international level) to produce the correct—*i.e.*, sustainable, safe, and responsible—results.

As leading experts and a prominent legal institution emphasize, (i) we need to take preventative action now at the national level because *we just won't reach international consensus in the short term,*[12] and (ii) it is critical to address the potential national harms at the licensing or market access stage, because those are "one of the rare decisions, if not the only one, taken by [a nation] which conditions the provision of [satellite] services" in its territory.[13]

Unless policy makers hold operators accountable for operating in a safe and sustainable manner, we are at serious risk of soon reaching a tipping point that leaves LEO unusable for decades, or even centuries. International organizations are starting to take note, but too little is being done. In the meantime, a small number of actors are racing to fill the sky and monopolize valuable orbits.

The key to avoid catastrophe is to reduce collision risk at the outset, by requiring LEO systems to operate within reasonable risk profiles. Each nation that authorizes systems to either occupy LEO or access its domains on, or above, Earth can define and enforce policies to ensure those systems are safe. Better space situational awareness and space traffic management are helpful—but like aviation on Earth, there are limits to the space traffic density that can be safely managed. The core issue is crowding too many objects into valuable regions of space by as few as one or two individual nations or commercial actors.

We need not accept these risks or consequences. Innovative systems can deliver better service, ensure space sustainability, and allow all nations to compete and fairly earn their place in the New Space economy. Analytical tools have been developed that allow us to understand the consequences of deploying certain LEO constellations before they are placed into orbit. National regulators have the power to ensure the systems they authorize

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[11] *Id.* ("While the debris problem is a significant consideration for the long-term use of orbital resources, such considerations may not play a significant role in economic decision making in the short-term. Individual satellite operators may have an interest in preserving the earth orbital environment for their continued operations, but a desire to avoid the short-term costs associated with deorbiting satellites to mitigate debris risk could override those long-term interests. Given these incentives, in the long term, the debris population is likely to continue to grow and could result in an exponential increase in the debris population such that use of certain valuable orbital configurations may no longer be economically feasible.").

[12] R. Buchs, Policy Options to Address Collision Risk from Space Debris, Lausanne: EPFL International Risk Governance Center (2021), at ii, https://infoscience.epfl.ch/record/290171?ln=en ("Given that the prospect of reaching consensus in the short term is very low, governments are advised to take unilateral but coordinated action by improving their national regulations.").

[13] Le Conseil d'État invalidation of Starlink market access, conclusions of rapporteur, Case No. 455321, April 5, 2022 (France).

or allow to serve their countries do not pose a threat to their own national interests, or to space safety, and that multiple actors can share the limited LEO orbital resources on an equitable basis.

I. Collision Risk and the Kessler Syndrome

The rapid pace of satellite launches intended to claim large swaths of LEO is raising awareness of the Kessler Syndrome. First postulated by NASA's Donald J. Kessler in 1978, a Kessler Syndrome occurs when positive feedback (*i.e.,* cascading collisions) leads to exponential growth in the space debris density. The debris density increases after each collision—increasing the rate of future collisions and further increasing the debris density until the collision rate becomes so high that all satellites are consumed. As discussed below, recent studies show this is a real threat because of the design of certain LEO mega-constellations.

The insidious nature of positive feedback is that we can reach a tipping point where a Kessler Syndrome becomes inevitable without even realizing it. If a tipping point is reached, all of humanity would watch helplessly as space junk multiplies uncontrollably. Without timely intervention, we risk bringing the Space Age to an inglorious end, and trapping humanity on Earth under a layer of its own trash for centuries, or even millennia. Not only an abrupt end to space exploration, but also the loss of all the benefits of space technology—including navigation, weather forecasting, climate measurements, and even satellite broadband (the intended purpose of the mega-constellations being deployed). Far from making humanity a multi-planetary species, a Kessler Syndrome would put an end to that vision.

Of course, growing an awareness of these risks is different from growing an understanding that enables timely and appropriate intervention. The combination of the irreversible consequences of a Kessler Syndrome and the accelerating pace of launches of mega-constellation satellites into LEO makes it imperative (as discussed further below) that we employ a model using quantitative metrics that help us understand both how close (or distant) we are to a tipping point and how rapidly we are approaching it. Those same metrics can also help us understand how to mitigate the situation—for instance by applying suitable space safety and sustainability requirements to a LEO constellation before it is allowed to serve a nation.

A Kessler Syndrome can be modeled to occur when the number of objects in space grows without bound, or equivalently, when the collision rate becomes infinite (Figure 1). Looking at the collision rate, and its derivatives with respect to the contributing factors, tells us which factors we must adjust to avoid catastrophe, or at least delay it (by shifting the curve substantially to the right).

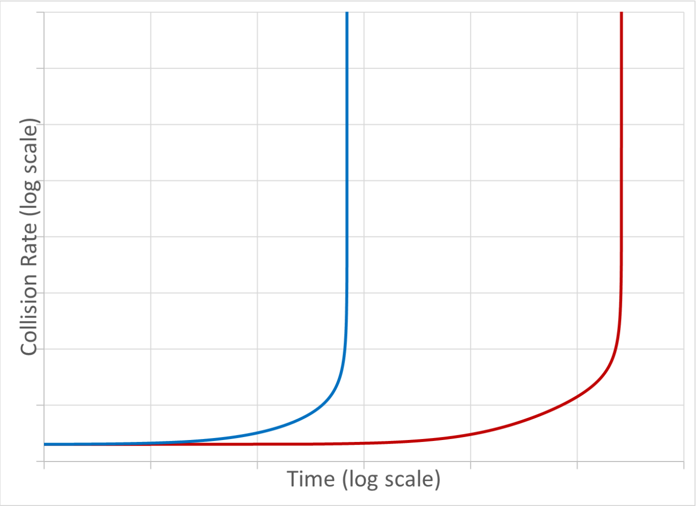

Figure 1. Log-Log Plot of Collision Rate vs. Time (Two Curves with Different Tipping Points)

Indeed, only through the quantitative measurements enabled by such a predictive model can we hope to understand what steps are needed to ensure that we can maximize use of limited and shared orbital resources, while also creating a safe and sustainable operating environment from which future generations can benefit.

Until we know where we stand, we risk merely treating the symptoms of the problem, and not addressing the root cause—especially if we focus on matters such as space traffic management (STM), space situational awareness (SSA), and the removal of large debris (such as rocket bodies) outside the context of a useful predictive model.

II. Assessing Collision Risk

LEO collision risks are appropriately analyzed over their orbital lifecycles. Large systems are incrementally deployed, and satellites are replenished as they fail, reach end-of-life, and are replaced with more capable models. This replenishment can be reasonably assumed to continue until the system is no longer economically viable. The result is a continuing process of orbit raising and phasing, and a combination of active and passive deorbiting. In addition, changes in the operating environment can be expected over a system's lifetime that increase collision risk, as more satellites are launched into LEO, as existing debris propagates, and as satellites breakup or explode.

As shown by the highlighted entries in Table 1, the operators of six large LEO constellations will individually receive from almost 1 million to over 10 million conjunction warnings per year, requiring from almost 100,000 to over 1.2 million maneuvers per year in attempting to avoid an aggregate of 695 collisions over 15 years that otherwise would be expected.[14] As the performance of space surveillance systems improves, the number of tracked objects will increase dramatically, to around 200,000 (from today's 24,243) as trackable size decreases from 10 cm down to 2 cm, increasing the average encounters in Table 1 by a factor of 8 to

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[14] SpaceX, as operator of its Gen1 and Gen2 Starlink constellations, would receive almost 11 million warnings per year (or an average of one every 3 seconds), requiring over 1.2 million maneuvers per year (or an average of one every 26 seconds) to avoid an average of 30 collisions per year.

12.[15] Despite allowing more objects to be avoided, this development would increase the burden on STM systems by an order of magnitude, increasing the opportunities for a human, software, or machine error to have catastrophic consequences.

Constellation	Altitude (km)	Inc. (°)	#Satellites	Average Encounters over 15 Years		
				Warnings	Maneuvers	Collisions
Amazon Kuiper	590 - 630	33 - 51.9	3,236	8,500,000	945,000	24
AST Science	700	98	243	1,460,000	163,000	4
Astra	380 - 700	0 - 98	13,620	24,154,000	2,685,900	67
Galaxy Space	500	63.5	1,000	4,430,000	493,000	12
Guangwang	508 - 1145	30 - 85	12,992	31,915,000	3,546,000	89
Hughes HVNET	1150	55	1,440	986,000	110,000	3
Iridium	778	86.4	75	725,000	80,400	2
Lynk	500	97.5	2,000	15,500,000	1,730,000	43
OneWeb	1200	55 - 87.9	716	2,168,000	241,100	6
OneWeb Gen2	1200	40 - 87.9	6,372	14,270,000	1,576,000	39
Sfera	870	98	640	4,860,000	540,000	14
SpaceX Gen1	540 - 570	53 - 97.6	4,408	75,420,000	8,366,000	209
SpaceX Gen2	340 - 614	33 - 148	29,988	86,314,000	9,914,600	248
SpaceX VLEO	335 - 346	42 - 53	7,518	7,760,000	861,000	22
SPIN	830	55	1,190	7,090,000	788,000	20
Telesat Gen2	1015 - 1329	50 - 99	1,671	1,380,000	153,800	4
Telesat Gen1	1015 - 1329	50 - 99	298	288,500	32,070	1

Table 1. Average Number of Encounters Over 15 Years (Current 24,243 Object Catalog)[16]

Every time an operator does not maneuver a satellite in response to a low probability conjunction warning, there is a non-zero collision risk. Additionally, every time an operator does maneuver, there is another non-zero probability that the maneuver will result in a collision. In both cases, with millions of conjunction warnings each year, even extremely rare ("six sigma") events can become likely.

Satellites that cannot maneuver cannot avoid collisions. This is true regardless of whether the collision is with other non-maneuverable satellites in the same LEO system, with a third party's inactive satellites, or with orbital debris of any shape or size.

Loss of maneuverability can result from failures of satellite subsystems in the maneuver chain (*e.g.,* propulsion, command) or from collisions that disable these subsystems. Failure risks can be mitigated with subsystem redundancy, space-qualification of components, and pre-launch testing. But not all such risks can be mitigated. It is generally recognized that

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[15] D. L. Oltrogge, Keeping Space Sustainable for Current and Future Generations, Space Generation Advisory Council (SGAC) Conference, Paris, France (Sep. 15, 2022), at 31, https://comspoc.com/Resources/Content/.

[16] Generated using COMSPOC's Number of Encounters Assessment Tool (NEAT), https://comspoc.com/neat/, on 15 October 2022 with constellation parameters from Dr. Jonathan McDowell's Space Pages, https://planet4589.org/space/stats/conlist.html, accessed 15 October 2022. NEAT's analysis is conservative in that it assesses only encounters with existing trackable space objects; it does not account for (i) encounters with lethal non-trackable debris (*i.e.,* smaller than 10 cm, as discussed below), (ii) the consequences of collisions, including the increase in, and spread of, new debris fragments caused by collisions, or (iii) the introduction of additional satellite constellations.

shielding is not a viable means of protecting commercial satellites against the consequences of collisions with the estimated 1,000,000 (and growing) pieces of debris between 1 cm and 10 cm that are unlikely to be tracked,[17] thus cannot be avoided, and which can render satellites non-maneuverable or even destroy them, fragmenting them into thousands of pieces. Collision risks with smaller objects (<1 cm) can be mitigated with appropriate design incorporating subsystem redundancy and shielding.

The 19,400 debris objects that are regularly tracked by Space Surveillance Networks[18] represent only a *tiny* percentage of all debris objects. The total number of debris objects estimated by statistical models and their potential effect on satellites with which they collide is shown in Table 2.[19]

Debris Object Size	Number in Orbit	Effect of Collision on Active Satellite
>10 cm	36,500	Catastrophic
1 cm to 10 cm	1,000,000	May be catastrophic or render it non-maneuverable
1 mm to 1 cm	130 million	May render it non-maneuverable

Table 2. Effects of Satellite Collisions with Debris

The debris environment naturally evolves over time as objects decay, active satellites become non-maneuverable (passive), and new objects are created by collisions between debris objects. Satellite collisions with large objects are typically catastrophic, fragmenting the objects and causing a step increase in the debris population, see Figure 2. In addition, upper stages and dispensers associated with the initial and replenishment launches add to the debris population.

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[17] European Space Agency, "Space Environment Statistics: Space Debris by the Numbers," last updated Aug. 11, 2022), https://sdup.esoc.esa.int/discosweb/statistics/.

[18] *See* Space-Track.Org.

[19] *Id.*

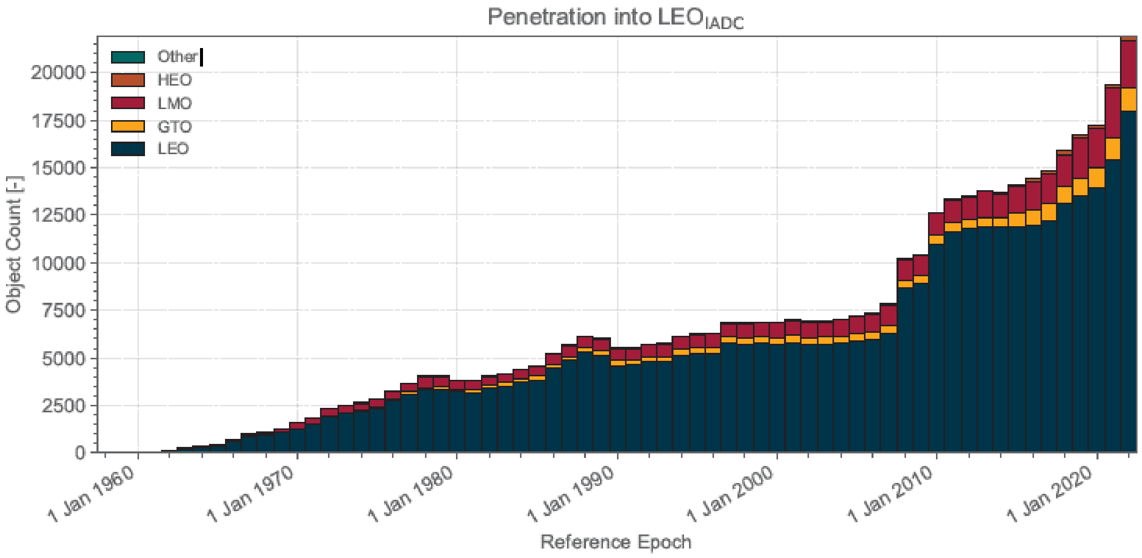

Figure 2. Continued Growth of Debris Environment[20]

Mitigating risks of failures with subsystem redundancy, and shielding to mitigate damage from collisions with small objects, are important, but perhaps more impactful is operational mitigation**:** For example, deorbiting satellites when reliability models cannot accurately predict when the maneuver chain may fail, and initiating deorbit immediately after the (N – 1)th failure with Nth redundancy.

III. Collision Consequences

Even with all reasonable mitigation, the reality of LEO mega-constellations is that the probability of catastrophic collisions occurring will increase. An important threshold question then becomes: What are the expected consequences of these collisions?

a. The nature of debris created by collisions

As demonstrated by a collision in LEO over 13 years ago, just two satellites colliding can create debris clouds consisting of many 1,000s of fragments that spread into orbits above and below the point of impact, and that persist for decades. More specifically, on February 10, 2009, the first collision involving two in-orbit satellites occurred. The active 689-kg Iridium 33 satellite collided with the passive 900-kg COSMOS 2251 satellite approximately 800 km above Siberia and produced an estimated 2,000 pieces of lethal trackable debris (>10 cm)[21] and many times that number of pieces of smaller lethal non-trackable (LNT) debris objects,[22] which have sufficient mass (given the impact velocity of LEO collisions) to fragment any satellites with which they collide. Thirteen years later, the remaining

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[20] ESA's Annual Space Environment Report (2022), at 21, https://www.sdo.esoc.esa.int/environment_report/Space_Environment_Report_latest.pdf.

[21] Fragments larger than 10 cm are typically observable by ground-based radars and telescopes, and hence are trackable. They are also massive enough to fragment any satellite they collide with. These are the lethal trackable fragments.

[22] B. Weeden, "2009 Iridium-Cosmos Collision Fact Sheet," Secure World Foundation, updated November 10, 2010, https://swfound.org/media/6575/swf_iridium_cosmos_collision_fact_sheet_updated_2012.pdf.

consequence of that collision is 1,342 trackable debris objects with apogees up to 1,650-km, spread across LEO, as depicted in Figure 3, plus a much larger number of LNT debris objects.

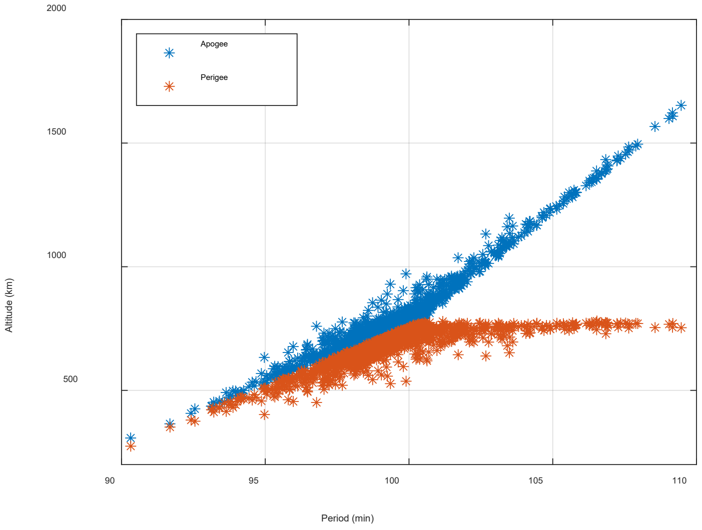


Figure 3. Spread of Lethal Trackable Space Debris from Iridium-33/Cosmos-2251 Collision

Attention has been drawn to the short-term and long-term consequences of a successful anti-satellite (ASAT) test that occurred in November 2021 with the COSMOS 1408 satellite. As shown in Figures 4 and 5, a similar result can be expected when two LEO satellites collide catastrophically.[23] Both types of events generate large numbers of lethal, *trackable* debris (Figure 4), and even larger numbers of *LNT debris* (Figure 5).

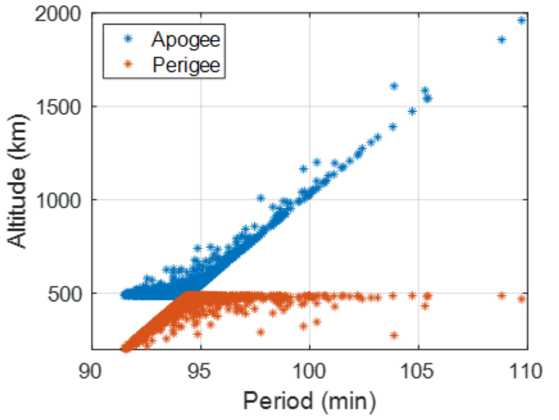
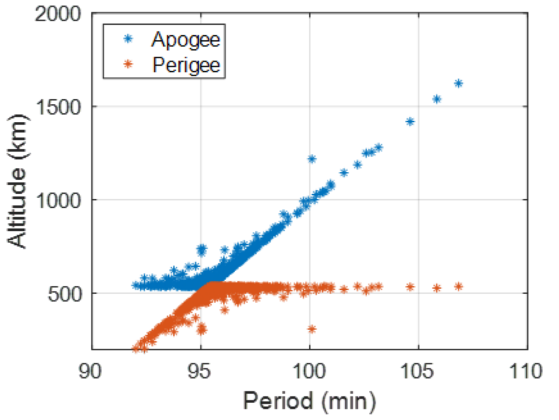
COSMOS-1408 ASAT Test	Starlink-Starlink Collision
	

Figure 4. Modeled Lethal Trackable Fragments from COSMOS-1408 ASAT Test (1,514 LT fragments) and Starlink-Starlink Collision (531 LT fragments)

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[23] *See Satellite Collisions Have the Same Consequences as ASAT Tests* (Nov. 2021), https://www.viasat.com/space-innovation/space-policy/space-debris/.

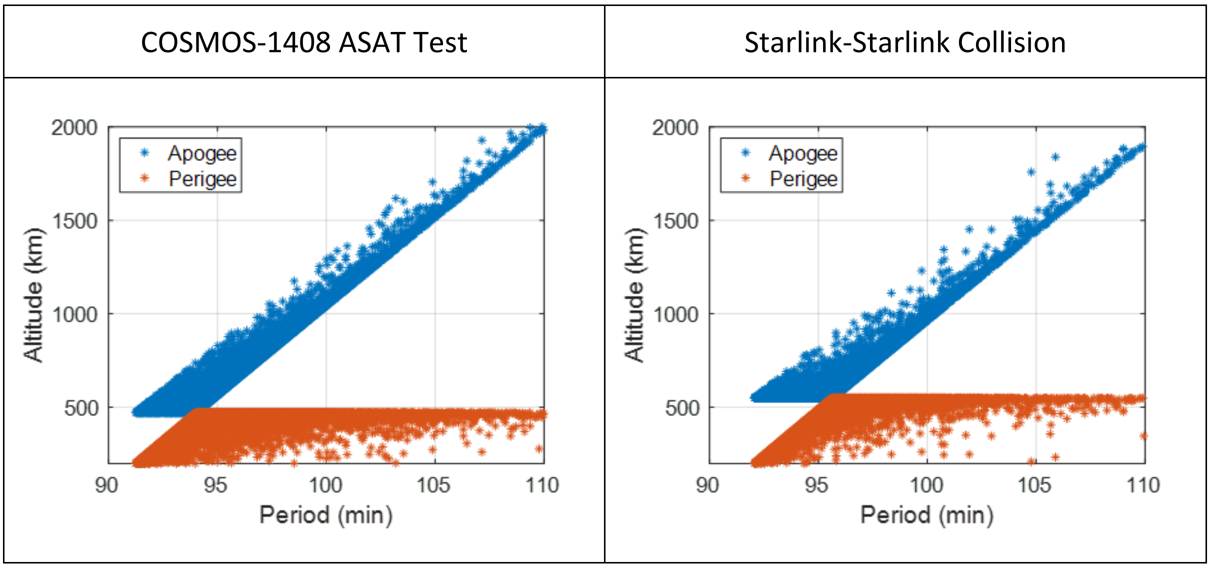

Figure 5. Modeled LNT Fragments from COSMOS-1408 ASAT Test (77,706 LNT fragments) and Starlink-Starlink Collision (26,968 LNT fragments)[24]

Debris fields of large numbers of lethal trackable fragments and even larger numbers of LNT fragments are characteristics of both accidental satellite collisions and successful ASAT tests. The exact numbers of fragments vary with multiple factors, including object masses. With all factors identical, the consequences of satellite collisions and successful ASAT tests are indistinguishable, posing a threat to LEO satellites, the International Space Station (ISS), and other space systems for decades, or even centuries.

These observations are particularly noteworthy because (i) LNT increase the risk of spacecraft collisions (and human casualties in space), (ii) LNT cannot be seen and thus cannot be avoided, (iii) the risks LNT create cannot otherwise be mitigated today, (iv) the amount of LNT already dwarfs all other forms of debris, (v) LNT are likely to be the fastest growing category of debris, (vi) LNT have a broad range of impacts on active satellites, and (vii) LNT are most dangerous to the fastest-growing category of small LEO satellites. In fact, experts explain that LNT "dominates the risk profile of operational spacecraft."[25]

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[24] Starlinks are used for illustration, as they are the most numerous of the large LEO constellation satellites with about 3,300 in orbit, and a 15-year license from the FCC to maintain 4,408 operating satellites plus an unlimited additional number that could be undergoing orbit raising or deorbiting at any given time. Very simplistically, given the numbers, if a satellite were to collide with a lethal debris object, it would more likely than not be a Starlink. The 260 kg version of the Starlink design in used in this illustration. The expected number of fragments would be over five times greater with the 2,000 kg version now being proposed.

[25] *See generally* R. Buchs, *Collision risk from space debris: Current status, challenges and response strategies* (Lausanne: EPFL International Risk Governance Center, 2021), at 13, *https://go.epfl.ch/irgc_space_debris_report* ("LNT objects dominate the risk profile of operational spacecraft. As they are far more numerous than trackable objects and cannot be avoided, LNT objects make up more than 95% of the mission terminating collisional risk for a typical LEO satellite[.]").

b. The persistence and consequences of debris created by collisions

A study entitled "Consequences of LEO Satellite Collisions – The Fragments" [26] analyzes the following questions in the context of the LEO mega-constellations being proposed and deployed:

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

This study shows that even collisions occurring below 600 km can have decades long consequences across a large swath of LEO.[27] Moreover, this study, along with other analyses,[28] lay bare the recurring misrepresentations that the portion of these orbits between 500 km and 600 km in altitude is intrinsically "self-cleaning," and that collisions among maneuverable or non-maneuverable (derelict) satellites in such orbits are therefore inconsequential. In reality, LEO satellite collisions at these altitudes have consequences that persist for decades because of the time it takes fragments from those collisions to decay, as shown in Figure 6.

Figure 6 shows the decay times for various fractions of the lethal trackable and LNT fragments from a catastrophic collision for each of the current Starlink orbits.[29] The curves show the time required for 90%, 99%, and 99.9% of the fragments to "clean-out." Collisions in these orbits have consequences for decades.

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[26] M. A. Sturza and G. Saura Carretero, Consequences of LEO Satellite Collisions – The Fragments (2021), 11th IAASS Conference – Managing Risk in Space, https://www.viasat.com/space-innovation/space-policy/space-debris/. This study uses the NASA Breakup Model and Blitzer decay model. Orbital parameter and area-to-mass ratio distributions are used to characterize the initial fragment clouds. Those distributions are then propagated over time using drag models to determine trajectories and orbital lifetimes.

[27] Passive decay times are longer for fragments than those of the original satellites because of the fragment orbits and area-to-mass ratios.

[28] *See Self-Cleaning Orbit Myth*, https://www.viasat.com/space-innovation/space-policy/space-debris/.

[29] SpaceX currently is licensed by the U.S. FCC to operate with nominal altitudes of 540, 550, 560, and 570-km, and tolerances that allow the orbits to vary as much as +/- 30 km in altitude.

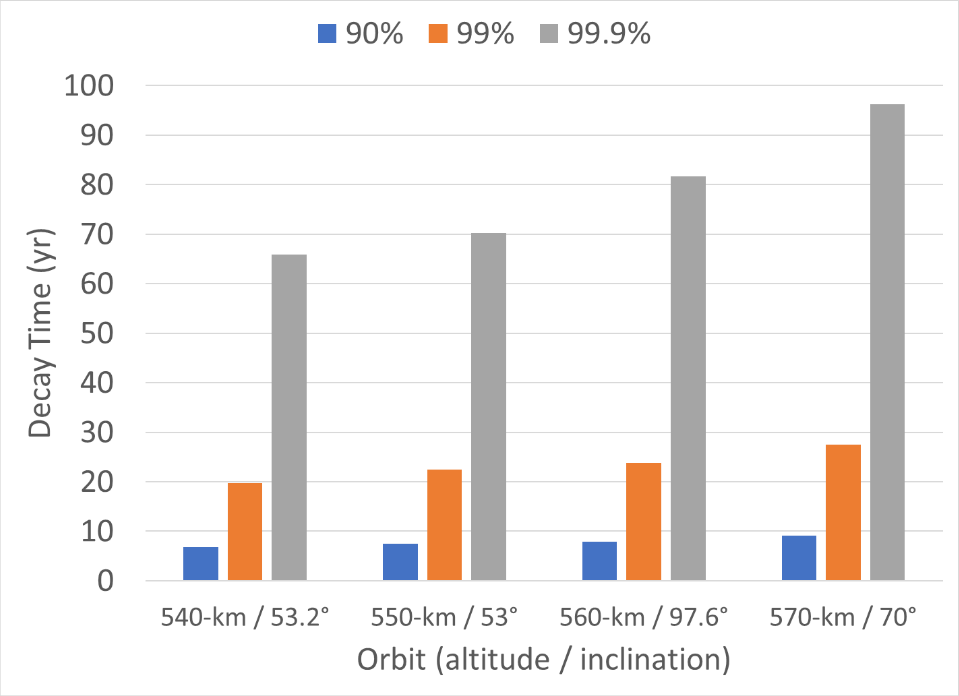

Figure 6. Decay Time for Various Fractions of Debris vs. Orbit

The “Consequences of LEO Satellite Collisions” study also shows that the consequences of collisions decrease dramatically with the mass of the satellites involved. That is, collisions between smaller satellites, such as 25 kg CubeSats, have significantly less consequence than collisions between two more massive (*e.g.*, 250 kg) 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. Thus, collisions between two 25 kg CubeSats are much less of a concern than those between two 250 kg satellites.

Unfortunately, LEO spacecraft are becoming larger and more massive, with significant implications for the space sustainability and safety risks posed by individual satellites, even when viewed in isolation (*e.g.,* per-satellite collision risks), due to increased collision risk associated with greater cross-sectional area, and the larger resulting debris fields when these satellites collide with other space objects.

The dramatic increase in satellite mass and cross-sectional area in LEO satellite designs is illustrated in the Figure 7. *As discussed below, this trend has serious repercussions for others who seek to access and use space*.

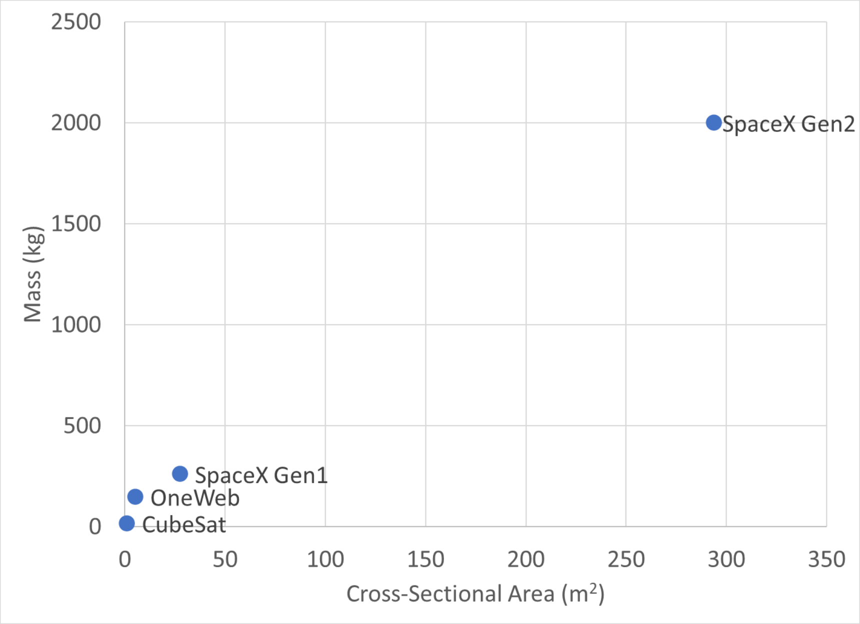

Figure 7. Trends in Estimated LEO Spacecraft Mass and Cross-Sectional Area

IV. Modeling Limits That Exist on Use of LEO

Other recent studies indicate that limits exist on what can sustainably occupy LEO, and that those limits depend on the specific characteristics of each LEO system and the impact of a steadily worsening space debris environment, including the impact of the large and growing quantity of space debris. In particular, the characteristics of LEO satellites (including cross-sectional area and mass) are one significant factor in assessing: (i) collision risk, (ii) how much additional debris collisions are likely to create—including the lethality and dispersion of that debris, and (iii) the precursor conditions and triggers that lead to a Kessler Syndrome.

One early study commissioned by the U.S. National Science Foundation (NSF) indicates that it may not be feasible to sustain even just one of the LEO systems already being proposed, and currently launching, and that individual mega-constellations may consume all, or most, of the limited LEO orbital "real estate" that must be shared by all nations globally. That study predicts the consequences of fully deploying one individual LEO system that has commenced deployment and ultimately seeks to consist of over 40,000 satellites at altitudes in the neighborhood of 600 kilometers. The study forecasts a dramatic increase in both space collisions and new debris, starting within just a few years. In the longer term, the NSF study predicts that "satellites are destroyed [by collisions with debris] faster than they are launched."[30]

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[30] G. Long, The Impacts of Large Constellations of Satellites, JASON – The MITRE Corporation, JSR-20-2H, Nov. 2020, (Updated: Jan. 21, 2021), at 97, https://www.nsf.gov/news/special_reports/jasonreportconstellations/JSR-20-2H_The_Impacts_of_Large_Constellations_of_Satellites_508.pdf.

Another study concluded that "Kessler Syndrome is expected to occur in low-Earth orbit around 2048 under recent historical sectoral growth trends, and may occur as early as 2035 if the space economy grows consistent with projections by major investment banks."[31]

The analytical concepts employed in the NSF study have been enhanced in another study using even more detailed models and simulations to explore more fully the sequences of events leading to a Kessler Syndrome as a function of the key parameters of large LEO constellations (the number of satellites, the satellite cross-sectional area and mass, and the density of those objects in specific orbits).[32]

That study, entitled "Design Trades for Environmentally Friendly Broadband LEO Satellite Systems," demonstrates the very real constraints that exist on the use of LEO. Namely, LEO has a limited orbital capacity (number and type of satellites that sustainably can be deployed), and a tipping point exists at which it no longer would be possible to avoid a Kessler Syndrome by ceasing launches.

That design trade study also shows that large LEO constellations of small satellites (<25 kg) are significantly safer to deploy than constellations of larger satellites. *This observation about the impact of satellite size on overall safety is extremely important in enabling the limited orbital capacity of LEO to be shared sustainably by all nations, globally*.

Crucially, that study illustrates that a tipping point is likely to be reached before existing measurement tools and observations are able to detect that a catastrophe is imminent.

Further modeling, using empirical measurement tools, and quantitative analyses, has been developed to help us understand the limits to LEO space exploitation and how we best can operate within those limits.

A research study entitled "LEO Capacity Modeling for Sustainable Design"[33] estimates LEO "carrying capacity," that is, the sustainable satellite population distribution in LEO. It estimates future debris propagation, considering both existing debris and the likelihood that non-debris objects become debris within a given time horizon. It also accounts for the performances of various possible mitigations.[34] This methodology enables holistically

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[31] A. Rao and G. Rondina, Open access to orbit and runaway space debris growth, arXiv:2202.07442 [econ.GN] (Feb. 16, 2022), at 1, https://arxiv.org/pdf/2202.07442.pdf.

[32] M. A. Sturza and G. Saura Carretero, Design Trades for Environmentally Friendly Broadband LEO Satellite Systems (2021), *2021 Advanced Maui Optical and Space Surveillance Technologies Conference (AMOS)*, https://amostech.com/TechnicalPapers/2021/Poster/Sturza.pdf.

[33] M. Sturza, M. Dankberg, W. Blount, LEO Capacity Modeling for Sustainable Design, Advanced Maui Optical and Space Surveillance Technologies Conference, Sept. 27-30, 2022, https://amostech.com/TechnicalPapers/2022/Space-Debris/Sturza.pdf.

[34] More specifically, this model includes a quantification of: (i) reasonable, estimates of unsuccessful mitigation attempts among active, maneuverable space objects, (ii) collisions with both trackable and untrackable debris and the effects of those collisions, (iii) dispersion of debris from collisions and the effects of that constantly evolving debris flux density, (iv) measurement (space situational awareness) uncertainty, including for objects and debris otherwise considered "trackable," and (v) growth in debris and debris flux density in critical orbital regions, such as, but not limited to, collisions among

comparing contributions to debris propagation as a function of specific system characteristics and deducing the incremental impact of individual systems and characteristics on LEO carrying capacity.

This research study yields a number of significant results: (i) the proposed second-generation configurations of two particular mega-constellation would consume all, or nearly all, of the carrying capacity in orbits neighboring those occupied by those constellations, (ii) less massive satellites and smaller cross-sectional area facilitate greater carrying capacity, and (iii) removing the existing population of derelict rocket bodies does not result in a material increase in LEO carrying capacity.

These results highlight the need to facilitate sustainable use of LEO by: (i) applying orbital admittance control and minimum satellite reliability requirements through license and market access conditions that limit the number of LEO satellites, mass, and cross-sectional area launched into various orbits, and ensure a certain probably of successful post-mission disposal; and (ii) developing suitable orbital regimes to support different types of LEO systems. For example, (a) altitudes below 400 km may be suitable for non-propulsive satellites; (b) altitudes in the 400 km to 600 km range may be suitable for mega-constellations (provided that the number of satellites, mass, and cross-sectional area launched are managed); and (c) smaller constellations above 600 km are likely sustainable depending on mass and cross-sectional area.

Significantly, the model underlying this research study is useful in: (i) assisting in the design of sustainable broadband LEO systems, (ii) assessing the impact of existing and planned LEO systems, and (iii) understanding the implications of multiple large LEO constellations occupying neighboring, interleaving, or overlapping orbits.

Moreover, using such a model can facilitate:

- Quantitatively measuring absolute and relative effectiveness of candidate regulations and policies governing space access and operations;
- Determining the effectiveness of remediations and mitigations such as specific forms of debris removal strategies, new post-mission disposal requirements, and anticipated improvements in Space Surveillance and Tracking (SST), Space Situational Awareness (SSA), and Space Traffic Management (STM);
- Considering interactions among all missions and constellations, instead of merely addressing each one individually and in the absence of all others and based on past or current debris flux models, and considering the debris flux that will exist over the lifetime of all those constellations;
- Determining the sensitivity of the LEO space environment to unanticipated events that might otherwise precipitate cascading collisions – such as the effects of surges

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uncontrollable/non-maneuverable objects including debris on debris (trackable or not), debris on non-maneuverable space objects, and non-maneuverable space objects interacting with each other.

in solar emissions reaching earth, unanticipated fragmentation of satellites in congested orbits, or even deliberate kinetic attacks; and

- Fostering identification of quantitative system design characteristics that slow, halt, or reverse acceleration towards a point in time when access to space is intolerably impaired or even lost.

Thus, such a model provides a quantitative alternative to intuitive heuristics and mitigations currently being contemplated. It should (i) provide for more informed policy making and licensing decisions, (ii) allow different researchers and administrations to understand, study, and reproduce the results of candidate rules, and (iii) enable adoption and data driven refinement of rules that have higher probability of success and that can be adjusted based on improvements in space safety technologies.

Notably, without employing a good predictive model, it is not possible to even recognize when a Kessler Syndrome is imminent or inevitable. Using a model allows us to "rewind" a possible sequence of events leading to a Kessler Syndrome—that is, look backwards from its occurrence to understand when a tipping point would have been reached and then carefully examine the state of LEO space at that point in time.

It bears emphasis that no predictive model should rely upon simplifying assumptions such as the existence of purported "self-cleaning orbits,"[35] a blind belief in the efficacy of "autonomous" controls in avoiding collisions,[36] or the fallacy that maneuverable satellites have "zero risk" of collision.[37] While many of the individual effects that must be quantified may be considered to be low probability with respect to individual objects, the large, and rapidly growing, number of trackable and untrackable debris objects, as well as predicted conjunction events, means that events that are low probability with respect to a single object are very likely to occur within the ensemble of all objects.

V. Market Forces Are Not Adequate to Mitigate Risks in LEO

Currently, the costs and risks created by certain LEO systems are being passed on to others, including other satellite broadband operators, and the science, defense, navigation, astronomy, and other industries whose operations in, or through, LEO are critical to many nations. The increased collision risk presented by certain LEO designs drives up the cost of access to space for everyone, whether in underserved areas or for the government itself (in the case of national defense use of space). In fact, cost/safety trade-offs are being made

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[35] See *Self-Cleaning Orbit Myth*, https://www.viasat.com/space-innovation/space- policy/space-debris.

[36] *See* Comments of NASA, U.S. FCC IBFS File No. SAT-AMD-20210818-00105 (filed Feb. 8, 2022), at 2 ("[T]he concern remains that other vendors proposing large constellations would also use auto-maneuvering capability within altitude ranges occupied by Starlink, thereby requiring multiple autonomous constellations to maneuver out of each other's way without clearly defined rules of the road for such interactions.") ("NASA Letter).

[37] *See id.* at 3 ("[C]onsidering multiple independent constellations of tens of thousands of spacecraft and the expected increase in the number of close encounters over time, *the assumption of zero risk from a system-level standpoint lacks statistical substantiation*.") (emphasis added).

today in certain LEO constellation designs, leading to the deployment of economically-expendable satellites that unduly increase risks for everyone. Among other things, those self-interested commercial decisions impair other uses of space by reducing the likelihood of successfully maneuvering to avoid collisions; or by compelling new entrants to use orbits that are less efficient, more expensive to reach or maintain; or by compelling much higher spacecraft design burdens than were used by earlier entrants that intentionally sought to impede competition by occupying more orbital real estate than warranted.

As the U.S. Federal Communications Commission recognized three years ago,[38] the economic incentives for some individual industry actors are not adequate to compel them to adopt responsible practices designed to ensure that the shared orbital environment remains available for all to use safely. Instead, these actors are motivated to adopt practices that force other space users to bear significant negative externalities, raising their economic costs and ultimately jeopardizing the continued viability of satellite operations, whether the others operate within LEO, or pass-through LEO on the way to or from other orbits. Moreover, the risk of business failure in this new environment is high, and business failures can leave an operator with neither the ability nor the incentive to promptly deorbit failed satellites.

One immediate consequence of the developing congestion in LEO is making even more scarce the number of viable launch windows that already are inherently limited[39]—and/or increasing the collision risks for those windows that remain. And the debris created by a collision involving LEO satellites, or even the mere presence in orbit of failed LEO satellites that are no longer maneuverable, will further impede the ability of other operators to launch their own satellites into orbit. At a minimum, these factors will increase the costs, risks, and delay associated with launching all satellites into space, as observed by the CEO of satellite launch provider RocketLab.[40]

This is why national administrations should adopt enforceable rules that discourage operators from emphasizing disposability and replaceability (redundancy in large numbers of satellites) rather than reliability and safety (deploying fewer and more efficient satellites that can be expected to be able to avoid collisions for the many years they remain in orbit). Absent such rules, operators: (i) will continue to make self-interested economic trades that endanger the sustainable and safe use of space; (ii) will not internalize the negative externalities created by their operations; and (iii) will not mitigate the burdens and adverse

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[38] *See* U.S. Federal Communications Commission, *Mitigation of Orbital Debris in the New Space Age*, Notice of Proposed Rulemaking, 18-159 (rel. Nov. 19, 2018), ¶¶ 88-89; Further Notice of Proposed Rulemaking, 20-54 (rel. Apr. 24, 2020), ¶ 25.

[39] NASA Letter at 4 ("NASA is also concerned with an increasing unavailability of safe launch windows, especially for missions requiring instantaneous or short launch windows, such as planetary missions like Europa Clipper, which would be significantly affected due to a lost launch opportunity.")

[40] J. Wattles, *Space is Becoming Too Crowded, Rocket Lab CEO Warns*, CNN (Oct. 8, 2020), https://www.cnn.com/2020/10/07/business/rocket-lab-debris-launch-traffic-scn/index.html ("Satellite constellations can be particularly problematic, he said, because the satellites can fly fairly close together, forming a sort of blockade that can prevent rockets from squeezing through.")

impacts that otherwise would be imposed on other operators and the public more generally.

VI. The Aggregate Risk Presented by Every LEO System Must be Considered

It is essential to assess the *aggregate* collision risk presented by *all* LEO systems that seek to serve, or use ground stations located in, a nation. As reflected in the studies referenced above, collision risk in LEO scales with factors such as cross-sectional area of the satellites, satellite mass, numbers and orbits of satellites, and satellite failure rates as they relate to maneuverability (*i.e.,* the capability to avoid collisions). There is an additive risk from each satellite in a given LEO system and each replacement that could be launched over the entire license term.

It also bears emphasis that because these parameters are the dominant determinants of space safety and sustainability, any effort by authorized operators to materially change those parameters for modified satellite designs should require a *re-evaluation* of the impact on aggregate collision risk based on a suitable demonstration by the operator *before* it is allowed to utilize such a modified design.

An aggregate collision risk evaluation should factor in the risks associated with derelict satellites that fail and no longer can maneuver, as well as the residual risks associated with the large numbers of maneuverable satellites due to conjunctions (*i.e.,* close calls) with both trackable and untrackable space debris and other active satellites that can be expected over a license term. This is true because a large number of even very low probability events (conjunction warnings with low probability that are not acted upon) results in multiple collisions realistically being expected over that timeframe.

Notably, the massive increase in LEO constellation sizes is driving an exponential increase in the number of conjunctions that a given constellation can be expected to experience over time—dramatically increasing the likelihood of an in-orbit collision that would have devastating impacts on space sustainability and safety.[41] As one leading expert explains: "The law of very large numbers will tell you that very low probability events can happen if given enough opportunities."[42] However, no current rules or guidelines reflect the magnitude of these dangers.

That means that these aggregate risk factors must be measured, assessed, modeled, and tracked, and operations adjusted, during the lifetime of each mission—not just at the initial authorization stage (including for communications and Earth observation missions).

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[41] NASA Letter at 1 (With the increase in large constellation proposals to the FCC, NASA has *concerns with the potential for a significant increase in the frequency of conjunction events and possible impacts to NASA's science and human spaceflight missions*."); ("An increase of this magnitude into these confined altitude bands inherently brings *additional risk of debris-generating collision events based on the number of objects alone.*) (emphasis added).

[42] *See* https://twitter.com/ProfHughLewis/status/1509903335251456045 (Apr. 1, 2022).

An appropriate evaluation of the entirety of the collision risk for a LEO system as a whole would include taking into account:

- Risks associated with derelict satellites that fail and no longer can maneuver (and therefore create significant risks for as long as they remain in orbit).
- The risks during the entire period each satellite in a mega-constellation remains in orbit and at all orbits it may populate (injection, operational, and post mission disposal).
- The increased risk of collisions due to changes in the orbital environment (such as satellites breaking up or exploding, debris colliding with other debris and breaking up further, and the deployment of additional LEO systems—not just the environment as it existed in the past).
- Characteristics of the system—cross-sectional area, mass, subsystem reliability, redundancy, shielding, and operational techniques to reduce the risk of system failures—and any subsequent proposed changes to those parameters.
- The risk of collisions with all sizes of space objects, whether trackable or not, including lethal non-trackable objects (LNT).
- The continued reliability of critical command and propulsion capabilities needed to try to maneuver to avoid collisions—and the probability that those critical systems may be damaged by untrackable debris that is too small to fragment the satellite.
- The risk of intra-system collisions within any of these LEO mega-constellations (due to all causes, including failed satellites).
- Known risks with large numbers (potentially millions per year) of expected conjunctions between a large LEO system and other space objects (*e.g*., large numbers of maneuvers to avoid some collisions create other collision risks; low probability conjunctions not resulting in avoidance maneuvers add up to much larger collision risks with very large numbers of conjunctions).
- The interactions of all satellites in a system with all other objects in their environment (including overlapping and intersecting orbits) during orbit raising maneuvers for rising satellites, considering active and passive decay trajectories for satellites in the orbital disposal phase, as well as taking into account those satellites in active service.
- The accuracy and tolerances of all orbital trajectories in order to accurately assess and model conjunction probabilities.

It is critical to develop a model to evaluate the current situation in LEO and the expected evolution of that environment. Observations and measurements today will not provide sufficient warning of the uses of LEO that could lead to self-sustaining, chain reactions of collisions that can destroy satellites and impair access to space for everyone for generations (a Kessler Syndrome). *Simply stated: We cannot know where we are with respect to LEO over-exploitation without a good model that can reliably forecast the evolution of debris in space.*

VII. LEO System Collision Risks Depend on the Numbers of Satellites

Some LEO operators try to downplay the significant collision risk with their systems by focusing on the risk of a single satellite and ignoring what can happen over the entire license term when hundreds, thousands, or tens of thousands, of satellites are operated at neighboring, overlapping, or intersecting altitudes. That approach ignores the simple fact that collision risk scales with constellation size. In other words, there is an additive risk from each satellite in a LEO system and the unlimited number of replacements that could be launched over the license term. Focusing on the risk of individual satellites in a constellation would effectively sanction catastrophic collisions occurring very frequently, as depicted in Table 3.

# of Satellites in Orbit	**Allowed Mean Time Between Collisions in Years (Days)**
1,000	5
5,000	1
10,000	0.5 (180 days)
50,000	0.1 (36 days)
100,000	0.05 (18 days)

Table 3. Aggregate Risk Applying a Single Satellite Risk Standard[43]

VIII. Collision Avoidance Systems Do Not Mitigate All Risks

Some try to downplay the aggregate risks of large LEO constellations by claiming that their LEO system will employ “autonomous” collision avoidance mechanisms. But the effectiveness of those capabilities depends entirely on each of their satellites being able to maneuver reliably and effectively for as long as the satellite remains in orbit—after injection, while at operational orbit, and throughout post-mission disposal. Satellites that fail or degrade such that they no longer can reliably be maneuvered cannot avoid collisions—with each other, with satellites in other systems, or with the large and growing amount of trackable space debris. For this reason, the deployment of unreliable LEO satellites presents undue risks to all who seek to utilize space.

If an operator launches tens of thousands of satellites with (for instance) even a 1% failure probability per satellite, it can expect to have *hundreds* of failed non-maneuverable satellites, rendering its autonomous avoidance system ineffective as to those satellite. There is no difference from a collision risk perspective between that cohort of hundreds of failed, non-maneuverable satellites and a different operator launching a similar number of satellites that are non-propulsive and/or non-maneuverable by design. They both have exactly the same result in space and yield the same collision risk probability. Moreover, conclusions about reliability cannot be drawn simply from “infant mortality” early in design life, because there is also a “wear out” failure mode that occurs near the end of design life.

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[43] Calculations are based on 5-year satellite design life, and application of the one-in-1,000 (0.001) collision risk standard commonly used for single-satellite risk scenarios.

Assessing the effectiveness of a collision avoidance system requires reliability analysis data on the satellites that demonstrates a suitable reliability performance level.

Furthermore, the mere existence of collision avoidance systems ("autonomous" or otherwise) does *not* mean there is a zero probability of collision. Models from Analytical Graphics, Inc. (a leading provider of collision-threat analysis tools) and others[44] show that crowding even tens of thousands of new satellites into LEO can generate hundreds of millions of total conjunction events over the license terms of LEO mega-constellations. The non-zero residual remaining collision probability, even after a maneuver is attempted, can be a significant contributor to Kessler Syndrome risk in the aggregate, given a sufficiently high number of conjunction opportunities. Moreover, the deployment of a mere one-third of a *single* mega-constellation is expected to account for 90% of all close approaches between two satellites,[45] and with the significantly increasing level of activity in LEO, experts warn that "changes will need to be made to make space more sustainable."[46] As discussed above, the law of very large numbers reinforces the need to use realistic models that help us predict the circumstances leading to potential catastrophes.

In addition, and as NASA has recognized, any automated collision avoidance system must be coupled with the capability to coordinate effectively with other operators in near-real-time so as "to ensure that intended maneuvers by either or both operators, if executed, do not place both satellites on a collision course."[47] But as third parties have noted, some LEO system collision avoidance processes do not incorporate this capability; rather, they incorporate features that are likely to frustrate inter-operator coordination and *exacerbate* collision risks.[48] Indeed, one LEO system operator has disclosed that its existing collision avoidance process: (i) does not incorporate any check to ensure that a planned maneuver to avoid one potential collision does not create an unacceptable risk of collision with other space objects (*e.g.,* another maneuverable satellite or orbital debris); and (ii) does not

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[44] S. Alfano, D. Oltrogge, R. Shepperd, Leo Constellation Encounter and Collision Rate Estimation: An Update, 2nd IAA Conference on Space Situational Awareness (ICSSA), Washington, D.C., Jan. 14-16, 2020, https://www.documentcloud.org/documents/6747529-LEO-CONSTELLATION-ENCOUNTER-and-COLLISION-RATE.html.

[45] T. Pultarova, *SpaceX Starlink satellites responsible for over half of close encounters in orbit, scientist says*, *Starlink satellites might soon be involved in 90% of close encounters between two spacecraft in low Earth orbit,* Space.com (Aug. 18, 2021), https://www.space.com/spacex-starlink-satellite-collision-alerts-on-the-rise.

[46] D. Swinhoe, *SpaceX's Starlink accounts for 'half of all satellite near misses'; Elon Musk's satellites coming within 1km of other companies' machines around 500 times per week,* Data Center Dynamics (Aug. 23, 2021), https://www.datacenterdynamics.com/en/news/spacexs-starlink-accounts-for-half-of-all-satellite-near-misses/.

[47] *See NASA Spacecraft Conjunction Assessment and Collision Avoidance Best Practices Handbook*, NASA/SP-20205011318 (2020), at 29, https://nodis3.gsfc.nasa.gov/OCE_docs/OCE_50.pdf.

[48] *See generally* https://twitter.com/planet4589/status/1429525312577183746 (providing various criticisms about autonomous collision systems, *e.g.* "So, the piece that seems to be missing—at least from this depiction—is the critical aspect of maneuver screening. You might plan a maneuver to mitigate a conjunction, only to create a worse situation. The burn plan needs to be screened against the catalog prior to execution.").

require interaction between operators prior to “autonomous” action by one or more of its LEO satellites.[49]

Another critical aspect of autonomous collision avoidance is whether other satellite operators are comfortable accepting the “autonomous” operator as the maneuvering agent when that operator has designed its system to employ economically expendable satellites such that it may not be as motivated to avoid collisions.

Industry experts note that the “right of way” to lanes, or maneuver options, in space may more appropriately be granted to those satellites that are most irreplaceable (economically or otherwise)—or at least be subject to conditions that preserve the rights of valuable, difficult to replace, space objects. In this respect, we emphasize that without any rules or constraints on the consumption of physical orbital resources, operators are motivated to keep poorly performing, or even failed, satellites in orbit in order to impede (or even preclude) access to those orbits by other operators. In contrast, with appropriate constraints on the use of orbital resources, operators would be motivated to keep in orbit only those satellites that contribute real value relative to the space they occupy.

At bottom, it is nearly impossible to attribute any value to an autonomous collision avoidance mechanism without having a comprehensive understanding of its intended and actual, empirically measured, performance. Much like the sophisticated risk models discussed above, assessing actual collision avoidance performance requires analysis, simulation, and a thorough evaluation of all live in-space maneuvers performed to date and the context in which they were performed.

IX. Other Environmental Issues

Growing concerns also exist about other environmental considerations when evaluating the finite nature of the shared LEO resource, its fragile nature, and the risk of over-exploitation.[50] Those include: (i) the potential for large quantities of satellites reentering the atmosphere to damage the Earth’s atmosphere and effect climate change through, among other things, radiative forcing,[51] and depletion of the ozone layer, increasing the risk of

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[49] *See* Letter from SpaceX to U.S. Federal Communications Commission, IB Docket No. 18-313, Att. B (Aug. 10, 2021).

[50] *See* Letter from Natural Resources Defense Council and the International Dark-Sky Association to U.S. Federal Communications Commission, IBFS File Nos. SAT-LOA-20200526-00055 and SAT-AMD-20210818-00105 (Sep. 7, 2022) (“NRDC & IDA Letter”).

[51] L. Organski, *et al.*, *Environmental Impacts of Satellites from Launch to Deorbit and the Green New Deal for the Space Enterprise*, Aerospace Corporation (Dec. 2020);

D. Werner, *Aerospace Corp. Raises Questions about Pollutants Produced during Satellite and Rocket Reentry,* SpaceNews (Dec. 15, 2020), https://spacenews.com/aerospace-agu-reentry-pollution/;

M. N. Ross & L. David, *An Underappreciated Danger of the New Space Age: Global Air Pollution, Scientific American* (Feb. 2021), https://www.scientificamerican.com/article/an-underappreciated-danger-of-the-new-space-age-global-air-pollution/;

M. N. Ross and K. L. Jones, Implications of a growing spaceflight industry: Climate change, JOURNAL OF SPACE SAFETY ENGINEERING (June 6, 2022), cancer and other negative health effects,[52] (ii) impairing critical optical and radio astronomical research by disrupting the visible night sky,[53] (iii) creating light pollution, with the resulting negative impacts on the health and quality of life of humans and on plants and animals,[54] and (iv) impairing the functioning of critical asteroid detection and defense capabilities.[55] In fact, certain choices made in LEO system design are the dominant factors affecting these additional impacts, such as satellite cross-sectional area, mass, orbit, and number of satellites, along with albedo (or reflectivity) and material composition.

We are trending the wrong way in each of these respects. Figure 8 shows the: (i) total number of satellites in LEO as of January 1, 2022,[56] as well as the associated mass and cross-sectional area of those satellites (in green) and (ii) the exponential increases in these values that would occur if merely the Starlink Gen2 system were allowed to deploy (in red).[57]

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https://www.sciencedirect.com/science/article/abs/pii/S2468896722000386;

U.S. Government Accountability Office, *Large Constellations of Satellites: Mitigating Environmental and Other Effects*, GAO-22-105166 (Sep. 29, 2022) ("First U.S. GAO Report"), https://www.gao.gov/products/gao-22-105166.

[52] NRDC & IDA Letter at 3.

[53] R. Boyle, *Satellite Constellations Are an Existential Threat for Astronomy*, Scientific American (Nov. 7, 2022), https://www.scientificamerican.com/article/satellite-constellations-are-an-existential-threat-for-astronomy/;

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C. Young, The worst case Starlink scenario? We could be 'right on the edge' of Kessler syndrome, INTERESTING ENGINEERING (Aug. 11, 2022), https://interestingengineering.com/innovation/worst-case-starlink-scenario-kessler-syndrome;

First U.S. GAO Report at 1;

United Nations Office for Outer Space Affairs, International Astronomical Union, IAC, NOIR Lab, Dark and Quiet Skies for Science and Society: Report and Recommendations, (Dec. 29, 2020), https://www.iau.org/static/publications/dqskies-book-29-12-20.pdf.

[54] NRDC & IDA Letter at 3.

[55] NASA Letter at 3 ("[T]here would be a Starlink in every single asteroid survey image taken for planetary defense against hazardous asteroid impacts, decreasing asteroid survey effectiveness by rendering portions of images unusable. This could … have a *detrimental effect on our planet's ability to detect and possibly redirect a potentially catastrophic impact.*") (emphasis added).

[56] *See ESA's Annual Space Environment Report*, at 52-54 (Apr. 22, 2022), https://www.sdo.esoc.esa.int/environment_report/Space_Environment_Report_latest.pdf (providing data used for Jan. 1, 2022 "baseline").

[57] Based on data SpaceX provided to the FCC in its pending modification to expand its system.

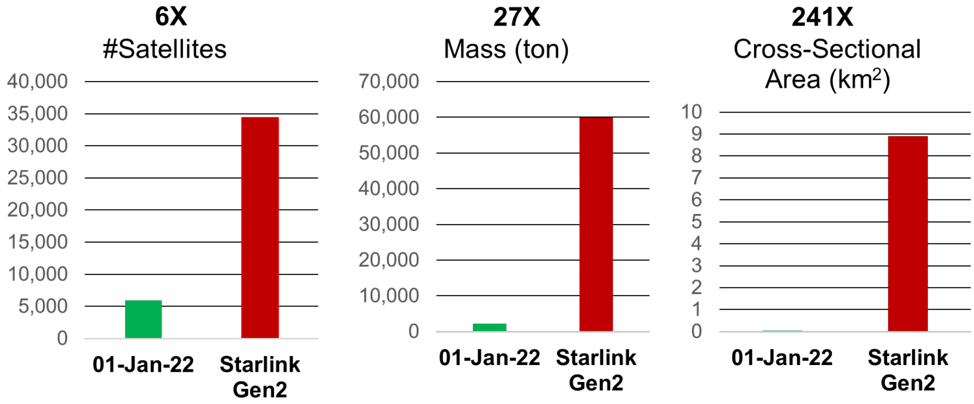

Figure 8. Trends in LEO Constellation Size, Mass, and Cross-Sectional Area

Expert review confirms that the decades-old approach being applied by some to the environmental effects of today's mega-constellations must be revisited to account for the new information that is available about those never-before-contemplated effects.[58] It is essential that these effects, as well as the exacerbating factors discussed above, be taken into consideration when evaluating limits on what can sustainably occupy LEO space from an environmental perspective.

X. Conclusion

It is critical to develop and adopt a robust legal and regulatory framework that helps ensure safe and sustainable uses of space; responsible constellation and spacecraft design must be a critical focus of that endeavor. Indeed, unless national policymakers hold operators accountable for safe space, we are at serious risk of soon reaching a tipping point that could leave LEO unusable for decades, or even centuries.

Notably, innovative LEO system designs can minimize these risks, while also delivering better service, ensuring space sustainability, and allowing all nations to compete and fairly earn their place in the New Space economy. The capability exists to ensure that the LEO systems that serve a given nation are not a threat to its national interests, or to space safety and the environment more generally.

We must act now, possibly even limiting the scale of individual mega-constellations, until we understand the consequences. Then we can take steps to ensure that a Kessler Syndrome tipping point remains sufficiently far in the future:

- Apply at the licensing and market access stages a model that evaluates the current situation in LEO, the expected evolution of that environment, and the consequences of launching additional LEO satellites.

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[58] U.S. Government Accountability Office, *FCC Should Reexamine Its Environmental Review Process for Large Constellations of Satellites,* GAO-23-105005 (Nov. 2022), at 28, https://www.gao.gov/products/gao-23-105005.

- Avoid simplifying assumptions such as the existence of purported “self-cleaning orbits,” a blind belief in the efficacy of “autonomous” controls in avoiding collisions, and avoid relying on the fallacy that maneuverable satellites have “zero risk” of collision.
- Reduce the cross-sectional area of LEO satellites, to reduce the probability of collisions even with lethal, non-trackable debris that cannot be avoided.
- Reduce LEO satellite mass, to minimize the consequence of collisions.
- Minimize the number of non-maneuverable satellites (passive satellites) in orbit that, by definition, cannot avoid collisions, including establishing methods and processes to actively de-orbit satellites before they can become non-maneuverable.
- Improve space situational awareness (SSA) accuracy to reduce the risk from conjunctions not resulting in avoidance maneuvers and also from maneuvering to avoid conjunctions.
- Have each nation that authorizes a LEO system to serve it ascertain that system’s potential impact on the environment, both in space and on the Earth, and whether it can share limited orbital resources on an equitable basis.
- Ultimately, establish binding and effective guidelines and practices among all space-faring nations to ensure safe, shared use of the limited LEO space.