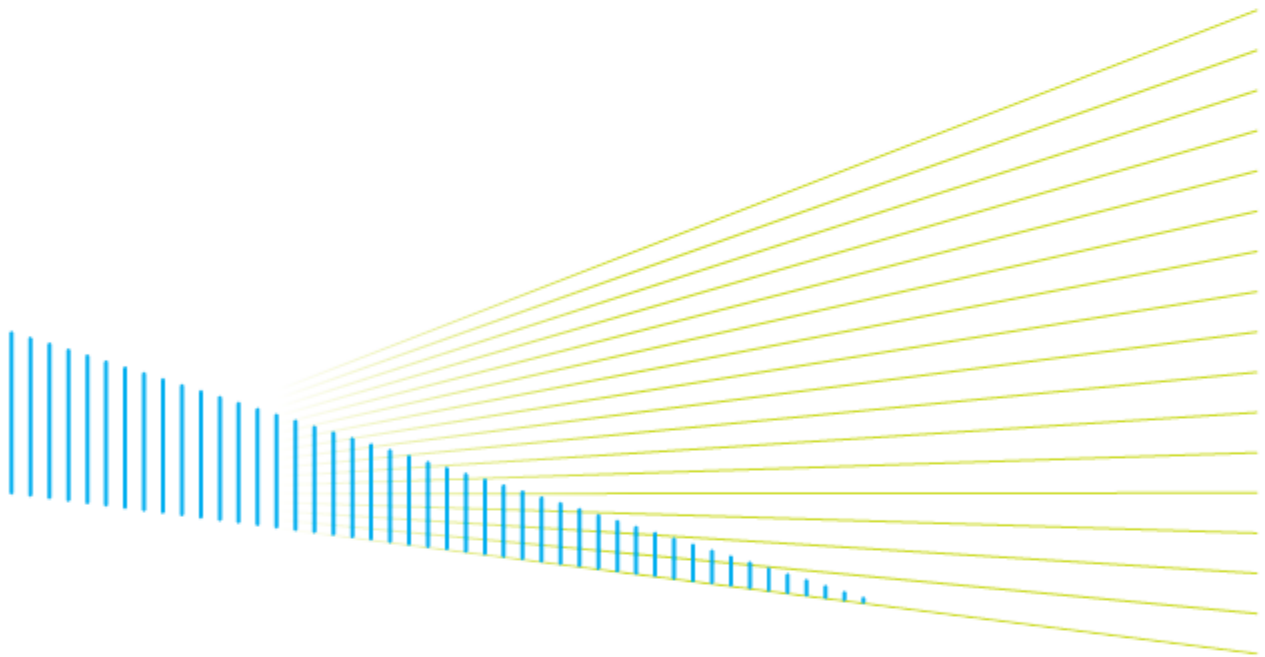


October 2021

Managing Mega-Constellation Risks in LEO



Introduction

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 area in space that can be used for human activities is a finite resource, fragile and at risk of over-exploitation, just like resources on Earth. And with exponential growth of space debris, the real estate in Low Earth Orbit (LEO) will not be big enough to support safe operation of an unlimited number of satellites.

Because of this, expert astrophysicists, scientists and regulators alike are expressing concern about growing orbital congestion in LEO and unduly risky behavior, both of which threaten not only today's space systems around the world, but also future space systems for commercial, defense, and scientific purposes:

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

“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

These experts are talking about (i) loss of safe access to LEO, and (ii) monopolization of orbital resources by a few actors. Their concerns 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 impact. 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

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

² H.E. Sarah 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>.

³ Dr. Moriba 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 Astrophysicist Dr. Jonathan McDowell, Harvard-Smithsonian Center for Astrophysics, <https://www.theverge.com/2021/1/27/22251127/elon-musk-bezos-amazon-billionaires-satellites-space>.

⁵ Mohammed 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/>.

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 large, and rapidly growing, number of trackable and untrackable space debris objects, and predicted conjunction events, 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.

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 little is being done. In the meantime, a few 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 do not have to accept these risks or consequences. Innovative new systems can deliver better service, ensure space sustainability, and allow all nations to compete and fairly earn their place in the New Space economy. National regulators have the power to ensure the systems they authorize 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.

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 not the same as 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 that we develop 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 requirements to a LEO constellation before it is allowed to serve a nation, and preemptively culling the most threatening maneuverable objects from those orbits at greatest risk—before they do harm.

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).

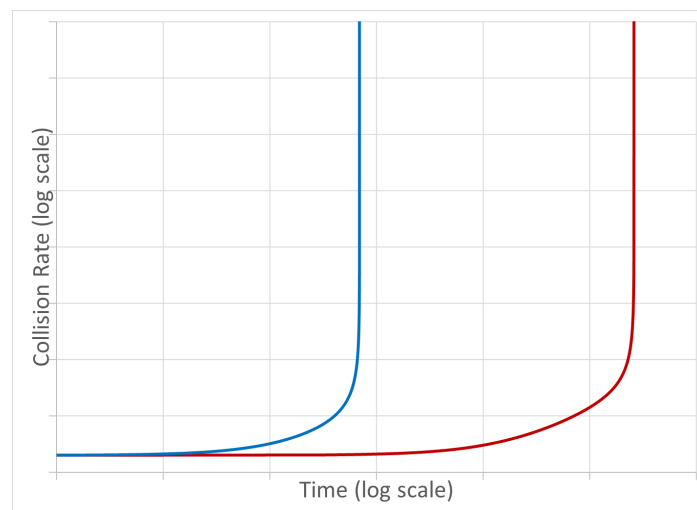


Figure 1. Log-Log Plot of Collision Rate vs. Time (Two Curves with Different Tipping Points)

Assessing Collision Risk

LEO system 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 modelled 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.

Operators of large LEO constellations will receive millions of conjunction warnings each year.⁶ 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 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,⁷ thus cannot be avoided, and that can render satellites non-maneuverable or even destroy them, fragmenting them into many pieces. Collision risks with small objects (<1 cm) can be mitigated with appropriate design incorporating subsystem redundancy and shielding.

The 29,510 debris objects that are regularly tracked by Space Surveillance Networks represents only a *very 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 1.⁸

⁶ 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, available at <https://www.documentcloud.org/documents/6747529-LEO-CONSTELLATION-ENCOUNTER-and-COLLISION-RATE.html>.

⁷ European Space Agency, "Space Environment Statistics: Space Debris By The Numbers," last updated Sept. 20, 2021), <https://sdup.esoc.esa.int/discosweb/statistics/>.

⁸ *Id.*

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	330 million	May render it non-maneuverable

Table 1. 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.

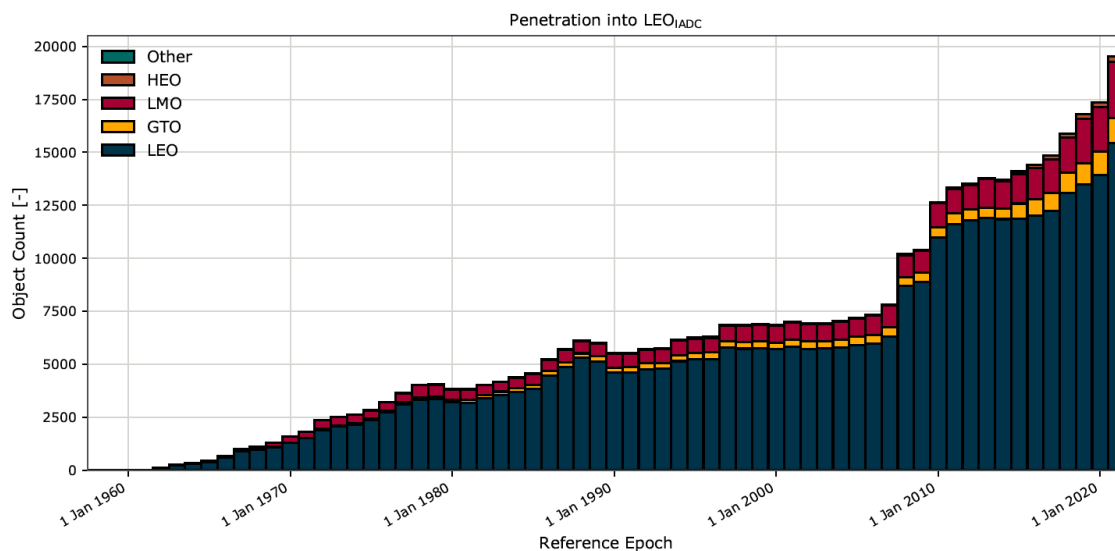


Figure 2. Continued Growth of Debris Environment⁹

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.

⁹ ESA’s Annual Space Environment Report (2021), at 21, available at: https://www.sdo.esoc.esa.int/environment_report/Space_Environment_Report_latest.pdf.

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?

As demonstrated by a collision in LEO over 12 years ago, just two satellites colliding can create a debris cloud 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 satellite occurred. The active 689-kg Iridium 33 satellite collided with the passive 900-kg COMOS 2251 satellite approximately 800 km above Siberia and produced an estimated 2,000 pieces of trackable debris (>10 cm) and many thousands of pieces of smaller but lethal non-trackable (LNT) debris objects.¹⁰ Twelve years later, the remaining consequence of that collision is 1,427 trackable debris objects with apogees up to 1,650-km, spread across many orbits, as depicted in Figure 3, plus a much larger number of LNT debris objects.

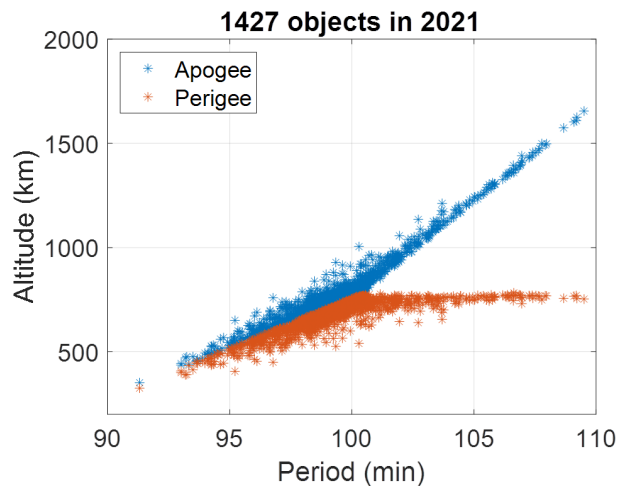


Figure 3. Spread of Space Debris from Iridium-33/Cosmos-2251 Collision

A recent study¹¹ analyzes the following questions in the context of the LEO mega-constellations being proposed and deployed:

- What can be expected when two large LEO system 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?

¹⁰ 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.

¹¹ M. A. Sturza and G. Saura Carretero, Consequences of LEO Satellite Collisions – The Fragments (2021), 11th IAASS Conference – Managing Risk in Space, available at <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.

This study shows that even collisions occurring below 600 km can have decades, or even centuries, long consequences across a large swath of LEO altitudes.¹² It 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.

Limits 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 amount 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 the Kessler Syndrome.

One notable 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 that 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 debris and collisions] faster than they are launched.”¹³

The analytical concepts employed in that NSF study have been enhanced in a new 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).¹⁴

¹² Passive decay times are longer for fragments than those of the original satellites because of the fragment orbits and area-to-mass ratios.

¹³ G. Long, *The Impacts of Large Constellations of Satellites*, JASON – The MITRE Corporation, JSR-20-2H, Nov. 2020, (Updated: Jan. 21, 2021), at 97, available at https://www.nsf.gov/news/special_reports/jasonreportconstellations/JSR-20-2H_The_Impacts_of_Large_Constellations_of_Satellites_508.pdf.

¹⁴ 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)*, available at <https://amostech.com/TechnicalPapers/2021/Poster/Sturza.pdf>.

That new study 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 study also shows that large LEO constellations of small satellites (<25 kg) are significantly safer to deploy than constellations of medium (25 to 300 kg) or large (>300 kg) satellites, see Figure 4. *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.*

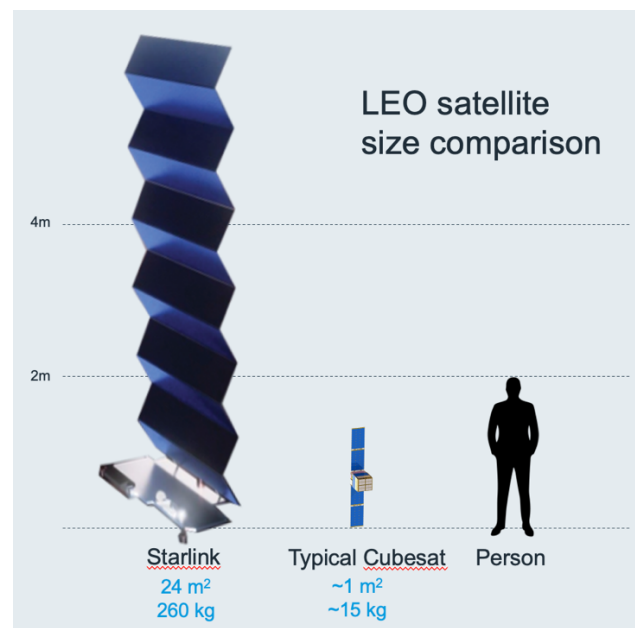


Figure 4. Visual Satellite Size Comparison

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. That means new models, measurement tools, and analyses are essential to understanding the limits to LEO space exploitation.

Such an analytical approach 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. Indeed, without a good predictive model, it is not possible to even recognize when a Kessler Syndrome is imminent or inevitable.

One important benefit of developing a sufficiently detailed model to evaluate these consequences is that it can let us “rewind” the sequence of events leading to a Kessler Syndrome—that is, look backwards from its occurrence to understand when a tipping point was reached and then carefully examine the state of LEO space at that point in time.

Such a model must include a quantification of all relevant effects, including: (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 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.

Significantly, a suitable predictive model should not rely upon simplifying assumptions such as the existence of purported “self-cleaning orbits,” the efficacy of “autonomous” controls in avoiding collisions, or the fallacy that maneuverable satellites have “zero risk” of collision. 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.

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 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 (FCC) recognized three years ago,¹⁵ 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

¹⁵ See United States Federal Communications Commission (FCC), *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.

operations, whether the others operate within LEO, or pass through LEO on the way to or from other orbits.

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—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.¹⁶

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 *reevaluation* 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 (conjunctions that result in avoidance maneuvers only if a certain risk threshold is exceeded) means multiple collisions realistically can be expected over that timeframe. That means that risks 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).

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

¹⁶ J. Wattle, *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.”)

- The risks during the entire period each satellite in a LEO 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.
- 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, within that system).
- 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 those orbital trajectories must also be understood 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.*

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 even 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 2:

# 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 2: Aggregate Risk Applying a Single Satellite Risk Standard¹⁷

Collision Avoidance Systems Do Not Mitigate All Risks

Some try to downplay these aggregate risks 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.

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 others¹⁸ show that crowding even tens of thousands of new satellites into LEO can generate hundreds of millions or billions 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, just a *single, partially-deployed* mega-constellation currently accounts for “half of all satellite near misses,” and experts warn that “changes will need to be made to make space more sustainable.”¹⁹ All of this reinforces the need for realistic models that help us predict the circumstances leading to potential catastrophes.

¹⁷ 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.

¹⁸ 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, available at <https://www.documentcloud.org/documents/6747529-LEO-CONSTELLATION-ENCOUNTER-and-COLLISION-RATE.html>.

¹⁹ D. Swinhoe, *SpaceX’s Starlink accounts for ‘half of all satellite near misses’; Elon Musk’s satellites coming*

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.”²⁰ 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.²¹ Indeed, one LEO system operator recently 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 require interaction between operators prior to “autonomous” action by one or more of its LEO satellites.²²

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 thorough, 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,

within 1km of other companies’ machines around 500 times per week, Data Center Dynamics (Aug. 23, 2021), available at <https://www.datacenterdynamics.com/en/news/spacexs-starlink-accounts-for-half-of-all-satellite-near-misses/>; see also 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), available at <https://www.space.com/spacex-starlink-satellite-collision-alerts-on-the-rise>.

²⁰ See *NASA Spacecraft Conjunction Assessment and Collision Avoidance Best Practices Handbook*, NASA/SP-20205011318, at 29 (2020), available at https://nodis3.gsfc.nasa.gov/OCE_docs/OCE_50.pdf.

²¹ 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.”).

²² See Letter from SpaceX to FCC, IB Docket No. 18-313, Att. B (Aug. 10, 2021).

simulation, and a thorough evaluation of all live in-space maneuvers performed to date and the context in which they were performed.

Other Relevant Issues

Growing concerns also exist about other considerations when evaluating the finite nature of the shared LEO resource, its fragile nature, and the risk of over-exploitation. Those include: (i) the potential for large quantities of satellites reentering the atmosphere to contribute to climate change through, among other things, radiative forcing and ozone depletion,²³ and (ii) the impact on optical astronomy, radio astronomy, and the visible night sky.²⁴ 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. These factors should be taken into consideration when evaluating limits on what can sustainably occupy LEO space.

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 new 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:

- Develop a model to evaluate fully the current situation in LEO, the expected evolution of that environment, and the consequences of launching additional LEO satellites.

²³ L. Organski, C. Barber, S. Barkfelt, M. Hobbs, R. Nakagawa, Dr. M. Ross, Dr. W. Ailor, *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), available at <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), available at <https://www.scientificamerican.com/article/an-underappreciated-danger-of-the-new-space-age-global-air-pollution/>.

²⁴ 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), available at <https://www.iau.org/static/publications/dqskies-book-29-12-20.pdf>.

- Avoid applying simplifying assumptions, such as the existence of purported “self-cleaning orbits,” the efficacy of “autonomous” controls in avoiding collisions, and 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 effective guidelines and practices among all space-faring nations to ensure safe, shared use of the limited LEO space.