January 15, 2021

BY ELECTRONIC FILING

Ms. Marlene H. Dortch
Secretary
Federal Communications Commission
45 L Street, NE
Washington, DC 20554

Re: Viasat, Inc. *Ex Parte* Presentation, IB Docket No. 18-313 and IBFS File Nos. SAT-MOD-20200417-00037 and SAT-MPL-20200526-00056

Dear Ms. Dortch:

Viasat, Inc. responds to the letter filed by Space Exploration Technologies Corp. ("SpaceX") on December 30, 2020. In its letter, SpaceX expresses a desire to "update the Commission's orbital debris rules to better account for the true cost of persistent debris"[1] and purports to compare the relative environmental costs of different non-geostationary orbit ("NGSO") system designs.[2]

Viasat agrees that the Commission's rules should account for the "true cost" associated with NGSO operations, but the bespoke proposal SpaceX advances is deeply flawed. Indeed, SpaceX's "aggregate risk years" proposal suffers from the same issues identified by Viasat in its letter of December 2, 2020—SpaceX fails to account for the factors that most directly affect the collision risk and environmental impact associated with each NGSO system.[3]

As summarized in Table 1 below and further detailed in Attachment 1, when all of the relevant factors are considered, the inescapable conclusion is that *each successive SpaceX modification of the Starlink constellation has increased collision risk*, not decreased it as SpaceX claims. And considering that each of the *existing and established* third-party metrics for

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1 Letter from SpaceX to FCC, IB Docket No. 18-313 and IBFS File No. SAT-MPL-20200526-00056, at 1 (Dec. 30, 2020) ("SpaceX Dec. 30 Letter").

2 *Id.* at 2-3.

3 *See* Letter from Viasat to FCC, IB Docket No. 18-313 and IBFS File No. SAT-MOD-20200417-00037 (Dec. 2, 2020) ("Viasat Dec. 2 Letter").

assessing collision risk illustrates the higher risks associated with Starlink, the Commission should be particularly skeptical about SpaceX's new proposed approach.

	DAS[4]		Kinetic Theory[5]	NEAT[6]
Constellation	Average Large Object Collision Probability	Expected Large Object Collisions Over Lifetime (MTBC)	Expected Intra-System Collisions Per Year (MTBC)	Expected Collisions Per Year Not Avoided (MTBC)
SpaceX 2016	2.22E-04	0.98 (5.1 years)	11.5 (32 days)	2.93 (0.52 years)
SpaceX 2018	2.67E-04	1.18 (4.3 years)	12.6 (29 days)	9.06 (0.11 years)
SpaceX 2020 (pending)	3.07E-04	1.35 (3.7 years)	14.5 (25 days)	10.88 (0.09 years)
Viasat LEO 288 (pending)	1.37E-04	0.04 (190 years)	0.077 (13 years)	0.152 6.58 years)

Table 1 – Mean Time Between Collisions (MTBC) Shows SpaceX Constellation Mods Reduce Space Safety and Viasat Constellation is Safer

The omissions and incorrect assumptions in SpaceX's assertions can be summarized as follows:

- SpaceX incorrectly assumes that NGSO operations at higher altitudes pose greater levels of persistent risk than operations at lower altitudes. This assumption is overly reductive and ignores significant complexities in the orbital environment—including the complex interplay between operations at different altitudes.

- SpaceX makes no effort to account for all, or even the most salient, factors impacting the "true cost of persistent debris." These are considerations with respect to Starlink that the Commission has not yet addressed, even though it has been over two years since the Commission first acknowledged the importance of reliability in the Starlink

[4] NASA's Debris Assessment Software (DAS). *See* NASA Technical Standard, Process for Limiting Orbital Debris, NASA-STD-8719.14B, 2019-04-25.

[5] The kinetic theory of gases has long been used to estimate satellite collision rates. *See* references collected in Attachement 1, Annex B.

[6] The Number of Encounters Assessment Tool (NEAT) was developed by AGI and assesses collision risk by adjusting key constellation parameters to estimate conjunction warnings, maneuvers, and collisions. *See* https://www.agi.com/missions/space-situational-awareness/what-s-the-number-of-encounters-assessment-tool-it.

syatem, and started a rulemaking proceeding to address rule changes necessitated by the New Space Age.[7]

- SpaceX does not account for *intra*-system collision risk in a system consisting of many thousands of satellites—perhaps the *most* significant factor, and one not included in the DAS analysis. This is very significant risk in SpaceX's case, particularly when one considers the persistent collision risk created by Starlink satellites that cannot reliably and effectively maneuver to avoid collisions, or be actively deorbited. There have already been dozens of instances of Starlink satellites that have lacked such maneuverability and reliability—including satellites launched within the past 6 months, as discussed below.

- The unprecedented number of conjunction events associated with Starlink's massive system of many thousands of satellites materially increases the overall "true cost" of this system. These conjunctions can be avoided only as long as: (i) they can be predicted with sufficient warning (and the provision of timely and accurate ephemeris data); (ii) SpaceX can plan and command avoidance maneuvers; and (iii) each Starlink satellite maintains a reliable and effective maneuverability and TT&C capability.

- The residual risks associated with *maneuverable* satellites in SpaceX's massive system lead to material numbers of expected collisions even if one assumes that, accounting for the uncertainty in orbit predictions, the maneuver threshold for a conjunction alert is very small in any given instance. In other words, this consideration reflects the cumulative collision risk associated with low-collision-risk conjunction warnings that do not result in actual avoidance maneuvers.

- SpaceX does not account for the collision risks that persist from the time a Starlink satellite no longer can be reliably and effectively maneuvered until the satellite's orbit passively decays (which can be as much as six years).

- SpaceX does not account for the risks that persist for decades once a Starlink satellite does collide with another space object 10 cm or larger, fragments, and spreads a debris cloud into orbits many hundreds of kilometers away, which adversely affects the operation of other satellite systems operating in, or traversing, those orbits.

- In addition, the bespoke "aggregate risk years" metric through which SpaceX attempts to operationalize its assumption about collision risk is highly flawed and arbitrary. Tellingly, SpaceX: (i) does not provide any clear methodology for

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[7] *See Space Exploration Holdings, LLC*, 33 FCC Rcd 3391, at ¶ 15 (2018) (agreeing with NASA that the unprecedented number of satellites proposed by SpaceX and the other NGSO FSS systems in this processing round will necessitate a further assessment of the appropriate reliability standards of these spacecraft") ("*SpaceX Initial Authorization Order*"); *Mitigation of Orbital Debris in the New Space Age*, Notice of Proposed Rulemaking, 33 FCC Rcd 11352 (2018).

> calculating this proposed metric; (ii) inexplicably utilizes different methodologies/formulas to calculate the metric for different systems (in a manner more favorable to SpaceX's system than other systems); (iii) does not explain how or why it arrived at the different formulas it appears to employ; and (iv) when purporting to measure the risk posed by Starlink, uses inputs that do not reflect the typical operational parameters of its system (leading to an unduly rosy picture of the risk posed by its system).

In short, there is no basis for the "aggregate risk years" metric proposed by SpaceX, which is ill-conceived and incomplete.

That said, Viasat appreciates that SpaceX at least acknowledges the need to account for the "true cost" of each NGSO system. This is a significant departure from SpaceX's previous advocacy, in which it has essentially encouraged the Commission to prioritize SpaceX's commercial interests above the public's interest in orbital safety. Among other things, SpaceX has opposed proposals (*e.g.*, the Commission's proposal to apply a 0.001 collision probability limit on an aggregate basis) that would require operators to properly internalize negative externalities and bear the "true cost" associated with their NGSO system operations.[8] Viasat hopes that SpaceX's letter signals a willingness to align its interests with the broader public interest.

Viasat also hopes that SpaceX's letter signals a new willingness to provide the Commission with the information needed to assess the "true cost" associated with SpaceX's own system. As the Commission knows, SpaceX's Starlink satellites have failed at an extraordinarily high rate. Indeed, recent independently developed data supports the conclusion that there has been a total of 79 failures[9] out of 953 Starlink satellites launched, representing an 8.3% failure rate.[10] Considering that SpaceX continues to rely on the launch of *all of those satellites* in its public interest advocacy,[11] it is only appropriate to include the impact of all Starlink satellites

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8 *See, e.g.*, Further Comments of Space Exploration Technologies Corp., IB Docket No. 18-313, at 3-7 (Oct. 9, 2020) (opposing Commission proposal to apply a 0.001 collision probability limit on an aggregate basis).

9 Defined to include satellites that were launched to provide service but never did.

10 *See* https://planet4589.org/space/stats/megacon/starbad.html (last visited Jan. 7, 2021). These failures have occurred over a mere fraction of the five-year design life of the Starlink satellites; the failure rate over that complete period is likely to be much higher. *See* Letter from Viasat to FCC, IBFS File No. SAT-MOD-20200417-0037, Att. at 4 (Jan. 7, 2020). Notably, Dr. McDowell's web site presents observed data for analysis and does not express a specific view on the failure rate of SpaceX satellites. *See* Letter from Viasat to FCC, IBFS File No. SAT-MOD-20200417-0037, at 1 (Sep. 24, 2020).

11 *See, e.g.*, Letter from SpaceX to FCC, IBFS File No. SAT-MOD-20200417-00037 and WT Docket RM-11768 (Dec. 28, 2020), Att. at 2 (claiming various benefits derived from the "955 Starlink satellites launched across 15 missions as of November 2020") ("SpaceX Dec. 28 Letter"). Particularly considering SpaceX's own advocacy, Viasat is not aware of any

when considering the public interest harms associated with Starlink. Only SpaceX can explain the aberrant performance and orbital behavior of over 8% of its satellites launched to date.

Failed satellites that have no ability to maneuver or avoid collisions with orbital debris, active satellites, or each other pose significant risks to space safety. Viasat has raised valid questions about the root cause(s) of these failures and what SpaceX is doing to address its flawed system design and/or construction,[12] but SpaceX has steadfastly refused to provide answers. Viasat can only hope that SpaceX's recent letter signals a newfound willingness to clarify the nature of its operations.

A. SpaceX incorrectly assumes that NGSO operations at higher altitudes pose greater levels of persistent risk than operations at lower altitude—ignoring significant complexities in the orbital environment

SpaceX asks the Commission to assume a direct correlation between the altitude at which an NGSO system operates and the risk of collision involving that system—*i.e.*, SpaceX advocates a metric at which operations at higher altitude would be assumed to pose greater risk. But SpaceX ignores significant complexities in the orbital environment, which render this approach deeply flawed, above and beyond its obvious self-serving nature.

As an initial matter, SpaceX's assertion that lower altitudes are less congested with space objects is simply incorrect. Figure 1 shows the number of tracked debris objects and rocket bodies by 100-km altitude bin based on Space-Track data as of January 6, 2021. These objects typically exceed 10 cm, and a satellite collision with any one of them would be catastrophic, fragmenting the satellite and creating more debris. As reflected in Figure 1, there are more tracked non-maneuverable objects in the 500-km to 600-km bin in which SpaceX plans to operate (495) than in either of the bins around 1,300-km where Viasat plans to operate (374 and 237).

Moreover, Figure 1 reflects over 7,000 debris objects in the 600 to 1000-km bins that would deorbit through the 500-600 km range in which Starlink satellites would operate, creating significant collision risks. Systems operating at higher altitudes do not face this risk to nearly the same extent. For example, there are only around 1,000 LEO debris objects above Viasat's proposed 1,300 km altitude, and it will take well over 100 years before those deorbiting debris objects could pose a potential risk to Viasat's satellites.

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valid basis for ignoring the v0.9 Starlink satellites (the first 60) when conducting a failure analysis, but even under such an approach, Starlink has suffered a 2.8% failure rate.

[12] *See* Letter from Viasat to FCC, IBFS File No. SAT-MOD-20200417-00037 and IB Docket No. 18-313, Annex (Dec. 21, 2020); *see also* Petition to Deny or Defer of Viasat, Inc, IBFS File No. SAT-MOD-20200417-00037 (Jul. 13, 2020); Reply of Viasat, Inc. in Support of Its Petition to Deny or Defer, IBFS File No. SAT-MOD-20200417-00037 (Aug. 7, 2020) ("Viasat Reply").

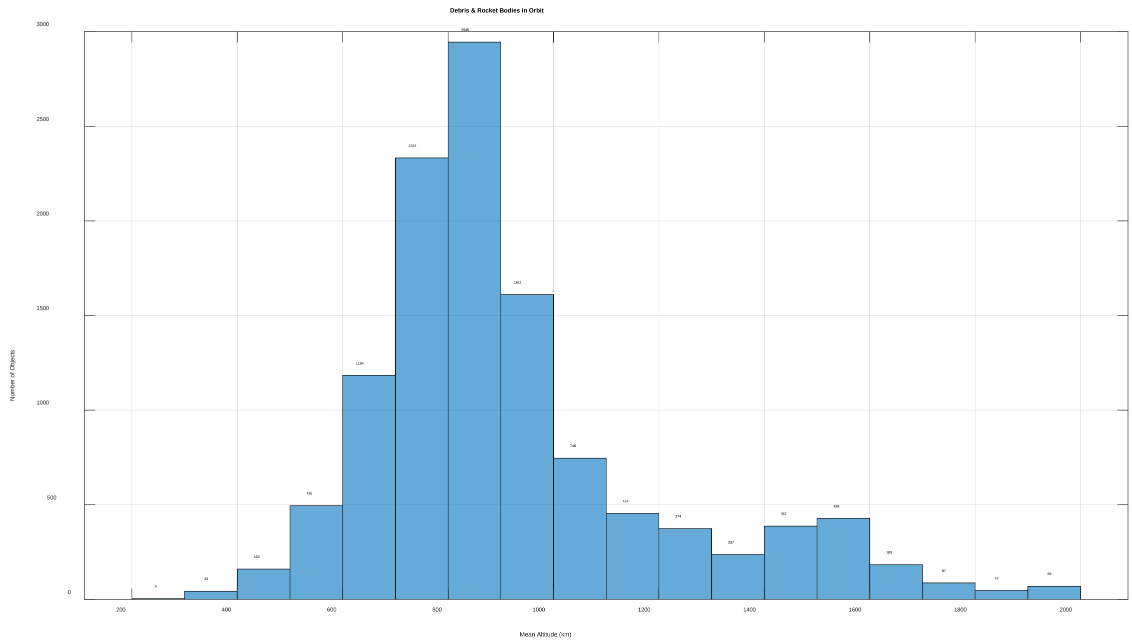

Figure 1 – LEO Tracked Debris Objects (including Rocket Bodies) by Altitude Bin

Not only is SpaceX incorrect in saying that the lower altitudes are less congested with space debris, but SpaceX does not factor in the additional collision risk posed by the satellites in proposed LEO constellations. Figure 2 compares estimated collision rates by altitude based on actual orbital objects in October 2019 and the estimated altitude-based collision rates taking into account the proposed LEO constellations (including Starlink). Note that the scales are different—the estimated collision rate in the 400 to 600-km regions *increases by approximately a factor of 250* when these new satellite constellations are introduced. At bottom, the collision risk is lower at higher altitudes because the orbital objects at those altitudes are further dispersed and there are few satellites operating in those regions. Also note that "satellites flown by the same operator were eliminated from encounter rate estimates in anticipation that an operator will properly ensure that their own spacecraft will not collide with each other."[13] This risk is discussed further below.

[13] Salvatore Alfano, Daniel L. Oltrogge, and Ryan Shepperd, *LEO Constellation Encounter and Collision Rate Estimation: An Update*, 2nd IAA Conference on Space Situational Awareness (ICSSA), Washington D.C., USA, IAA-ICSSA-20-0021.

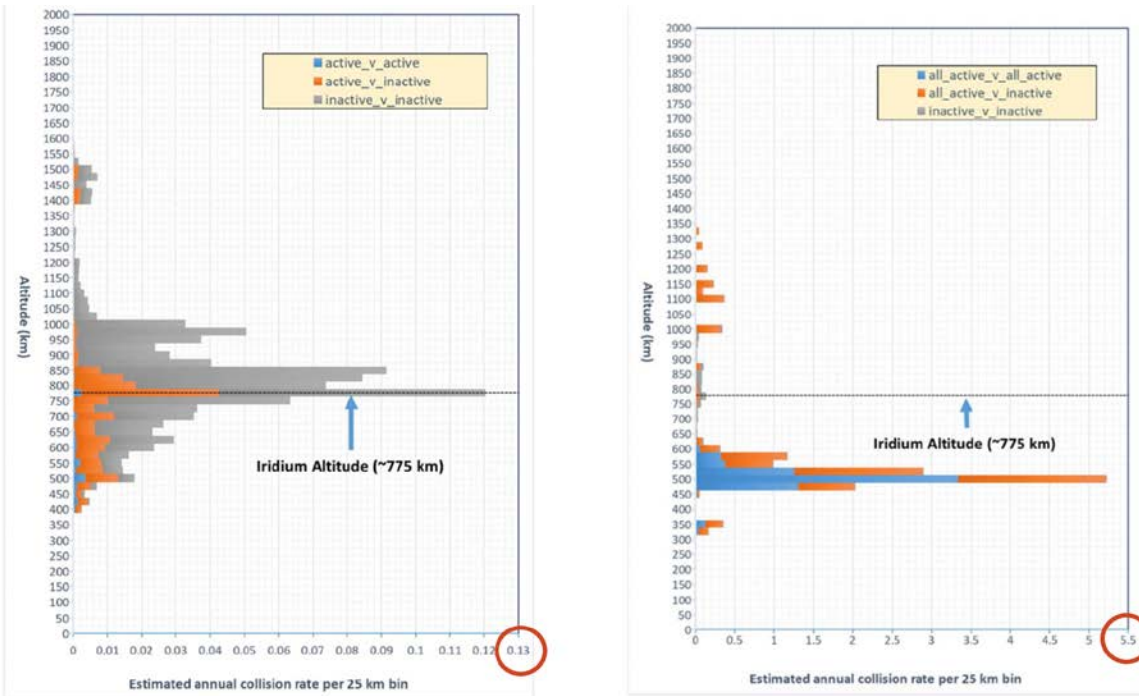

Fig. 2 Annual collision rates for October 29, 2019, 18 SPCS RSO catalogue

Annual collision rates (includes October 29, 2019 catalogue and proposed constellations)

Figure 2 – Estimated Collision Rates Before and After Launch of Proposed LEO Constellations[14]

Also incorrect is SpaceX's assertion that Starlink satellites operating at ~550 km decay in "just a few years" and thus do not pose significant risk.[15] As Viasat noted in its December 2, 2020 submission, these objects pose significant collision risk for as long as they remain in orbit—*e.g.*, in the case of a failed Starlink satellite that is incapable of maneuvering and avoiding potential collisions—which could be as long as 6 years.[16] And when they do collide and fragment, these failed satellites have the potential to create large debris fields that will remain in orbit *for decades or even a century of more* (as reflected in the following Table 2):

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14 *Id*.

15 SpaceX Dec. 30 Letter at 2.

16 *See* Viasat Dec. 2 Letter at 2; *see also* Viasat Reply at 9-11.

Apogee (km)	Decay Time
550	13.7 years
650	17.8 years
750	28.6 years
850	42.9 years
950	59.9 years
1050	79.7 years
1150	96.5 years
1250	> 100 years
1350	> 100 years

Table 2: Passive Decay Times for Collision Fragments in Various LEO Orbits with 550 km Perigee[17]

In addition, SpaceX's approach ignores the complex interplay between operations at different altitudes, and how the operations of one system can impact the collision risks faced by other systems (at much higher or lower altitudes). Notably, a fragmentation event in LEO can be expected to create a significant number of debris objects that will impact altitudes over hundreds of kilometers—not just those at the collision altitude. For example, the entirely unexpected February 10, 2009 Iridium-33/Cosmos-2251 collision created 2,294 trackable debris objects, 1,396 of which remain in orbit 12 years later.[18] These debris objects were spread to orbits over 800-km higher, as shown in Figure 3.

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[17] *See id.* at 9-15. The decay times in this table are computed assuming a 550-km perigee and 0.01 m^2/kg area-to-mass ratio for fragmentation debris created in 2020. The lower area-to-mass ratio typical of fragmentation debris results in a much longer decay time compared to that of an intact Starlink satellite.

[18] *See* https://fragmentation.esoc.esa.int/home/statistics (last visited Jan. 7, 2021).

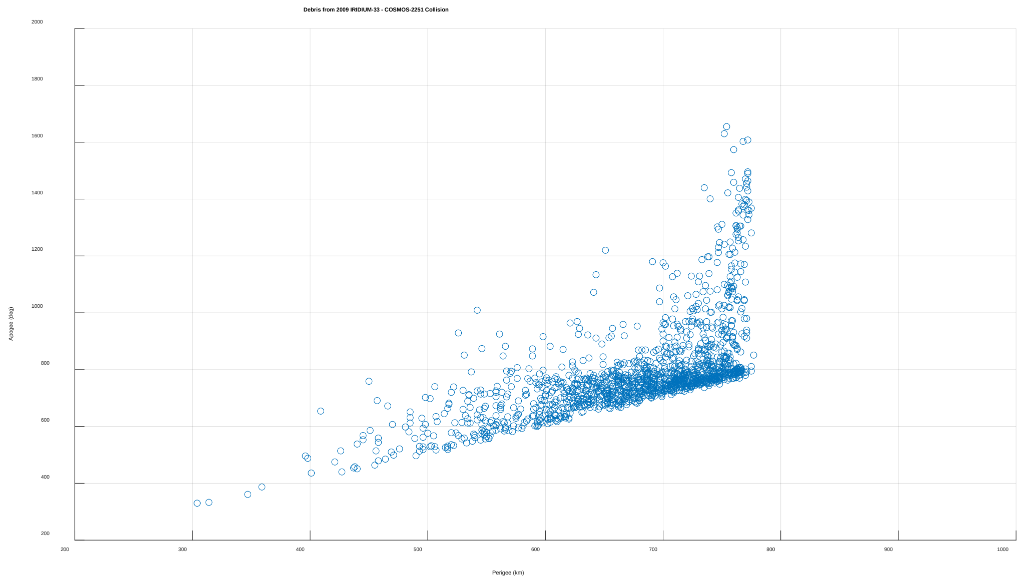

Figure 3 – Spread of Debris from Iridium-33/Cosmos-2251 Collision[19]

The following Table 3 was prepared using DAS as detailed in Attachment 1, Annex A. It compares the average probability of per satellite large object collisions, the expected number of collisions per constellation over satellite lifetime, and the mean time between collisions for various SpaceX constellations, and for the Viasat LEO constellation. It is seen that SpaceX's system has become more dangerous after each constellation modification, from an average of one collision every 5.1 years to one every 3.7 years. Viasat's LEO is seen to be over 40 times safer, with an average of one collision every 190 years.

	Average Probability	Expected Collisions	Mean Time Between Collisions
SpaceX 2016	2.22E-04	0.98	5.1 years
SpaceX 2018	2.67E-04	1.18	4.3 years
SpaceX 2020 (pending)	3.07E-04	1.35	3.7 years
Viasat LEO 288	1.37E-04	0.04	190 years

Table 3 – Average Probability of Per Satellite Large Object Collisions, Expected Number of Collisions Per Constellation over Satellite Lifetime, and Mean Time Between Collisions

Notably, the issues discussed above, and in the following sections, include short- to medium-term effects on space and access to space by other satellite systems that operate outside the Starlink orbits. They go to the heart of the reason that the Commission made the policy

[19] Plotted from 6 January 2021 Space-Track data.

decision to regulate orbital debris and collision risk almost 17 year ago.[20] They are issues, however, that the Commission still has not addressed almost three years after issuing SpaceX its conditional license.[21]

B. SpaceX fails to account for the most salient factors impacting the "true cost of persistent debris"—including intra-system collision risk

Any metric designed to account for the "true cost of persistent debris" should account for the most salient factors impacting that cost. It is curious, then, that SpaceX does not account for *intra*-system collision risk in its advocacy.

Intra-system collision risk—*i.e.,* the risk that two or more satellites within a single system will collide—is not incorporated into the DAS model. Yet, as the record reflects, this risk is a significant component of the total collision risk posed by an NGSO system consisting of many thousands of satellites.

Intra-system collision risk can be calculated by applying the kinetic theory of gases (see Attachment 1, Annex B for a more fulsome explanation). Notably, there is significant literature supporting this approach (which is not the case with respect to the use of the "aggregate risk metric" proposed by SpaceX). This methodology was used to estimate intra-system collision rates for the original, modified, and proposed SpaceX NGSO systems. The results are shown in Table 4.

Constellation	**Expected Collisions Per Year**	**Mean Time Between Expected Collisions**
SpaceX 2016	11.5	0.087 years (32 days)
SpaceX 2018	12.6	0.080 years (29 days)
SpaceX 2020 (pending)	14.5	0.069 years (25 days)
Viasat LEO (pending)	0.077	13.03 years

Table 4 – Estimated Number of Intra-System Collisions Per Year

Significantly, it is seen that SpaceX's system has become more dangerous after each constellation modification, from an average of one collision every 32 days to one every 25 days. Viasat's LEO is seen to be almost 200 times safer, with an average of one collision every 13

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[20] *See Mitigation of Orbital Debris,* 17 FCC Rcd 5586 (2004).

[21] *Cf. Space Exploration Holdings, LLC,* IBFS File No. SAT-MOD-20200417-00037, DA 21-34, at ¶¶ 12 &40t (asserting that partial grant of authority to SpaceX "does not implicate" orbital debris concerns raised by commenting parties, and requiring SpaceX to obtain approval of an updated orbital debris mitigation plan before updating any other satellites) (Jan. 8, 2021); *SpaceX Initial Authorization Order* ¶¶ 40p & r.

years. While this approach to estimating collision rates is known to be conservative, it is an established and empirically sound basis on which to compare the relative risk presented by the two systems, including the prior and current Starlink designs. The key takeaways are that SpaceX is not improving safety with its modifications, and that SpaceX's systems with 4,408 satellites between 500- and 600-km altitudes has a two orders of magnitude higher intra-system collision rate than Viasat's 288 satellites at 1,300-km.

C. SpaceX ignores the risks associated with unprecedented number of conjunction events associated with its proposed NGSO system

As Viasat has previously demonstrated, the massive nature of the Starlink system leads to an enormous number of predicted conjunction events with space objects—potential collisions that must be monitored, evaluated, and, in many cases, avoided by effectively and reliably maneuvering the satellite (and not moving into the path of another space object and causing another collision in doing so).

Table 5 compares the estimated yearly warnings, avoidance maneuvers, and "collisions not avoided"[22] with mean-time-between-collisions (MTBC) for the original (SpaceX 2016), modified (SpaceX 2018), and modification pending (SpaceX 2020) SpaceX constellations and for Viasat's pending modified constellation. As detailed in Attachment 1, Annex C, these estimates were computed using the current catalog of 19,697 resident space objects that are 10 cm or larger in size and can result in "catastrophic" collisions[23] that would fragment the Starlink satellites. Notably, these estimates do not account for the significant growth in space objects in LEO that will be seen as proposed LEO constellations deploy. When all relevant factors are considered, the inescapable conclusion is that the numbers of warnings, maneuvers, and "collisions not avoided" increase with each SpaceX constellation modification. In all cases, they are significantly higher than those for the Viasat constellation.

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[22] The number of "collisions not avoided" is calculated taking into account that when a large number of conjunction alerts are not acted upon because they have a low probability of resulting in collisions, the cumulative collision risk can be significant.

[23] *See, e.g.*, R. Thompson, *A Space Debris Primer*, CROSSLINK (Fall 2015), at 5 (explaining that the impact from an object 10 cm and larger in diameter is the equivalent of a bomb blowing up inside the spacecraft); *see also* Comments of Viasat, Inc., IB Docket No. 18-313, Section III (Oct. 9, 2020).

	Warnings	Maneuvers	Collisions Not Avoided	MTBC
SpaceX 2016	216,602	24,067	1.9/year	0.52 years
SpaceX 2018	1,019,029	113,226	9.1/year	0.11 years
SpaceX 2020 (pending)	1,223,832	135,981	10.9/year	0.09 years
Viasat LEO 288 (pending)	7	1,900	0.15/year	6.58 years

Table 5 – Number of Encounters Assessment Tool (NEAT) Yearly Estimates forSpaceX and Viasat LEO Constellations[24]

Of course, both SpaceX and Viasat can be expected to initiate avoidance maneuvers as appropriate. With the pending modification, SpaceX could expect to receive over 3,350 warnings per day, over 370 of which might require planning and execution of avoidance maneuvers. In comparison, Viasat could expect to receive around 46 warnings per day, around 5 of which might require avoidance maneuvers.

Even if SpaceX could process 2.5 warnings per minute, and plan and actually execute an avoidance maneuver every four minutes, that leaves over 1 million warnings per year that would not be acted upon. The inherent uncertainty with orbit predictions means that some collisions still could occur even where avoidance maneuvers are not effectuated. Even using a very low maneuver threshold for a conjunction alert of a 0.00001 (1 in 100,000) probability of collision, with over 1 million alerts per year not acted upon, SpaceX would experience an average of 10.9 collisions per year, as detailed in Attachment 1, Annex C. That means 163 collisions could be expected over a 15-year license term, even if one assumes 100% reliability of the Starlink collision avoidance capability, which we know is not the case, given its experiential failure rate.

The ability to execute an avoidance maneuver requires that a Starlink satellite have reliable and effective maneuverability and TT&C during its entire orbital lifetime. Once a Starlink satellite loses reliable and effective maneuverability capability or TT&C, it is a collision risk until it passively deorbits. And as SpaceX's own calculations demonstrate, one of its failed satellites can remain in orbit for up to six years.[25] Furthermore, as is clear from the available evidence, a staggering number of Starlink satellites have failed, many of the failed satellites are or were not maneuverable, and a number of other Starlink satellites in orbit are exhibiting odd orbital behavior. Neither the Commission nor outside observers of the Starlink system know the reason that SpaceX has not been able to achieve the level of reliability it promised the Commission.[26]

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[24] *See supra* n.6.

[25] *See* Reply of Viasat, Inc. in Support of its Petition to Deny or Defer, IBFS File No. SAT-MOD-20200417-00037, at 11 (Aug. 7, 2020).

[26] *See, e.g.*, Letter from SpaceX to FCC, IBFS File No. SAT-LOA-20161115-00118, at 4 (filed April 20, 2017) (representing that "SpaceX will construct its spacecraft to specifications and tolerances to ensure that failure rates are nowhere near the [1, 5 or 10 percent] levels

There is no good reason to continue to speculate about the reliability or effectiveness of the maneuverability capability of *any* Starlink satellite. SpaceX relies on of all of its 955 satellites lauched to date in asserting the public interest benefits of its system.[27] The failures and unreliability experienced with each satellite within that 955 total correspondingly must be evaluated as part of the public interest analysis that the Commission is obligated to conduct. Consistent with its responsibilities, the Commission must independently investigate the circumstances surrounding the failures and unreliability of the Starlink satellites.

Moreover, under these circumstances there would be no basis on which to assume that the risk of a Starlink satellite colliding with another space object 10 cm or larger is zero or near zero.

D. The specific "aggregate risk years" metric proposed by SpaceX is highly flawed and arbitrary

In addition to all of the foregoing issues, the newly proposed metric—"aggregate risk years"—on which SpaceX relies has no basis in the Commission's rules, NASA's standards, or readily available scientific literature. Notably, SpaceX does not specify any methodology for calculating this bespoke metric, let alone justify any such methodology or the underlying components. Instead, SpaceX employs an unsubstantiated approach that minimizes the calculated risk posed by its own NGSO system, while unfairly depicting the risk posed by Viasat's proposed NGSO system or any other NGSO system operating at about 1,000 km.

Tellingly, SpaceX does not even calculate its own baseless metric in a consistent manner. In footnote 6 of its letter, SpaceX uses the following formula to calculate the "aggregate risk years" for Starlink:

> (1 – reliability factor) x (DAS calculated risk) x (some number of years) x (number of satellites)

But SpaceX inexplicably adds a factor of 200 when computing "aggregate risk years" for the Viasat system—which of course has the effect of artificially inflating the value SpaceX presents for Viasat's case. Specifically, footnote 7 of its letter uses the following formula to calculate "aggregate risk years" for Viasat:

> (1 – reliability factor) x (**<u>200 x</u>** DAS calculated risk) x (some number of years) x (number of satellites).[28]

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postulated in this question."); Letter from SpaceX to FCC, IBFS File No. SAT-LOA-20170301-00027, at 6-7 (Jul. 17, 2017) (assuming a failure rate of 1%, and explaining that a higher failure rate is "highly unlikely").

[27] *See, e.g.,* SpaceX Dec. 28 Letter, Att. at 2 (claiming various benefits derived from the "955 Starlink satellites launched across 15 missions as of November 2020").

[28] In footnote 7 of its letter, after stating that the "DAS-calculated Large Object Collision Risk" for Viasat's system is 3.11e-04, SpaceX uses a value of 6.22e-02 in its formula, 200 x 3.11e-

And SpaceX otherwise uses overly favorable parameters in calculating "aggregate risk years" for its own Starlink system. For example, SpaceX uses a DAS-calculated large object collision risk of 9.34e-5, even though the actual constellation-average per-satellite value is 30.7e-5—a factor of 3.3 larger.[29] SpaceX also assumes an average decay time of 1.72 years, when the actual value (averaging over solar cycles and orbit altitude) is around 3.5 years—a factor of 2 larger. Furthermore, SpaceX assumes a 98% reliability factor (2% failures over lifetime), while the experiential failure rate is 8.3% (when the v0.9 satellites are included as they are for SpaceX's other public interest advocacy)[30] at less than one fifth of average design lifetime. This is larger by a further factor of *4*. If these corrected Starlink parameters are plugged into the formula used in footnote 7, the calculated "aggregate risk years" value is 74, compared to the 0.014 value calculated in footnote 6. Put simply, SpaceX appears to have underrepresented the risk of its system by a factor of 5,200, even under its bespoke metric.

Although Viasat believes the "aggregate risk years" metric is of little value in any event, SpaceX's lack of integrity in applying its own flawed metric is very concerning.

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For the reasons set forth herein and in Viasat's letter of December 2, 2020, the Commission should reject the "aggregate risk years" proposal advanced by SpaceX. Instead, the Commission should apply the 0.001 collision probability limit on an aggregate basis, as proposed by the Commission and supported by Viasat and other parties. The Commission also should require SpaceX to address the many unanswered questions on the record about the design, manufacturing, and operation of its system.[31]

Respectfully submitted,

/s/
Amy R. Mehlman
Vice President
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Jarrett S. Taubman
Associate General Counsel
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04 = 6.22e-02. SpaceX provides no explanation for the factor of 200 and does not use it in footnote 6 of its letter with respect to its own system. As explained in Attachment A, Annex A, Viasat calculates a DAS value of only 1.37e-04 for its NGSO system.

29 *See* Attachment 1, Annex A. These values are calculated using the latest, 16 December 2020, solar flux table and a January 2021 launch date for comparison purposes.

30 *See supra* n.11 and accompanying text.

31 *See* Letter from Viasat to FCC, IBFS File No. SAT-MOD-20200417-0037, Annex (Dec. 22, 2020).

Attachment
SpaceX Modifications Increase Collision Risk

SpaceX claims that each of its modifications has increased space safety.[1] This is not the case; in fact, each of the SpaceX modifications has reduced space safety, increasing collision risk. SpaceX has also claimed that its constellation poses less risk than Viasat's. Again, this is not the case. The Viasat constellation is safer, and poses lower collision risk. Further, the Commission's recent decision to allow SpaceX to launch 10 satellites into sunsynchronous orbit has decreased space safety, and increased collision risk.

The original (SpaceX 2016), modified (SpaceX 2018), and modification pending (SpaceX 2020) SpaceX constellation orbits are shown in **Table 1**. Viasat's pending modified constellation consists of 288 satellites in planes at 1,300-km altitude and 45° inclination.

Table 1 – SpaceX Constellation Configurations

Number of Satellites	Inclination	Altitude	SpaceX 2016	SpaceX 2018	SpaceX 2020 (pending)
1600	53°	1150 km	X		
1600	53.8°	1110 km	X	X	
400	74°	1130 km	X	X	
375	81°	1275 km	X	X	
450	70°	1325 km	X	X	
1584	53°	550 km		X	X
1584	53.2°	540 km			X
720	70°	570 km			X
520	97.6°	560 km			X
Total Number of Satellites			4,425	4,409	4,408

This paper evaluates four metrics and compares them for the various constellations. The metrics are:

1. DAS calculated per satellite probability of large object (> 10 cm) collision, weighted average over the various shells of each constellation (see Annex A).
2. Expected number of collisions for each constellation, and the associated mean-time-between collisions (MTBC), based on DAS calculated probability of large object collisions (see Annex A).
3. Expected intra-system collision (self-collision) rate, and the associated MTBC, based on the kinetic theory of gases (see Annex B).

[1] *See. e.g.*, IBFS File No. SAT-MOD-20200417-00037, Narrative at ii (Apr. 17, 2020), (claiming that SpaceX's commitment to maintaining a clean orbital environment was a key driver behind its initial modification to lower its initial deployment and its decision to develop and deploy spacecraft with allegedly "no calculated casualty risk," and that the pending modification application seeks to "double down on the benefits of the lower altitude"). As detailed below, these assertions simply are not true.

4. Expected number of collisions, and MTBC, occurring considering low probability collision conjunction alerts that are not acted upon, based on NEAT calculations (see Annex C).

The metrics are compared in **Table 2**. For each metric it is seen that each SpaceX modification has increased, not decreased, collision risk. Also, it is seen that for each metric, the modified (pending) Viasat constellation poses significantly less collision risk than any of the SpaceX constellations.

Table 2 – SpaceX Constellation Mods Reduce Space Safety and Viasat Constellation is Safer

	DAS		Kinetic Theory	NEAT
Constellation	Average Large Object Collision Probability	Expected Large Object Collisions Over Lifetime (MTBC)	Expected Intra-System Collisions Per Year (MTBC)	Expected Collisions Per Year Not Avoided (MTBC)
SpaceX 2016	2.22E-04	0.98 (5.1 years)	11.5 (32 days)	2.93 (0.52 years)
SpaceX 2018	2.67E-04	1.18 (4.3 years)	12.6 (29 days)	9.06 (0.11 years)
SpaceX 2020 (pending)	3.07E-04	1.35 (3.7 years)	14.5 (25 days)	10.88 (0.09 years)
Viasat LEO 288 (pending)	1.37E-04	0.04 (190 years)	0.077 (13 years)	0.152 6.58 years)

The impact on space safety of relocating 10 SpaceX satellites from their original orbits to the 560-km, 97.6° shell is shown in **Table 3**. Regardless of which of the four planes they were moved from, risk increased. Specifically, all depending on which planes they were moved from:

- The DAS calculated large object collision probability and expected number of large object collisions over lifetime increased by a factor of 2.2 to 4.4.
- The expected number of intra-system collisions increased by a factor of 1.1 to 1.3.
- The expected number of collisions per year not avoided increased by a factor of 1.9 to 5.8.

While the magnitudes of these impacts, in terms of collisions per year, are small,[2] they are all in the same direction, and confirm that relocating the 10 satellites increased overall collision risk.

[2] Of course, the reason the magnitude of the impact is small is because only 10 satellites are involved. If operators of proposed mega-constellations were to scale those constellations down in size by two to three orders of magnitude, the space safety risk would be mitigated.

Table 3 – Relocation of 10 SpaceX Satellites Decreased Space Safety Regardless of Which Shell They Were Moved From

	DAS		Kinetic Theory	NEAT
Shell	Large Object Collision Probability	Expected Large Object Collisions Over Lifetime (MTBC)	Expected Intra-System Collisions Per Year (MTBC)	Expected Collisions Per Year Not Avoided (MTBC)
1,110-km, 53.8°	2.64e-4	0.0026 (1,893 years)	0.00021 (4,839 years)	0.0046 (218 years)
1,130-km, 74°	2.80e-4	0.0028 (1,787 years)	0.00019 (5,129 years)	0.0059 (169 years)
1,275-km, 81°	2.15e-4	0.0022 (2,323 years)	0.00019 (5,391 years)	0.0069 (145 years)
1,325-km, 70°	1.50e-4	0.0015 (3,338 years)	0.00018 (5,451 years)	0.0023 (432 years)
560-km, 97.6° (New shell)	4.41e-4	0.0044 (1,133 years)	0.00024 (4,219 years)	0.0133 (75 years)

Annex A
DAS Calculated Large Object Collisions

An intact satellite represents a relatively small collision risk to other users of space. A satellite fragmented by catastrophic collision presents a risk that can be orders of magnitude larger. Because of the high typical collision velocities (around 10 km/s in LEO), LEO satellite collisions with large debris objects (diameter ≥10 cm) are likely to cause catastrophic collisions.[3]

By keeping the uniform probability of collision with other large objects less than 0.001, NASA attempts to achieve its goal that the average probability will be less than 10^{-6} of any individual operating satellite colliding with a fragment >1 mm from a prior collision.

NASA's Debris Assessment Software (DAS) [4] provides a means of calculating the probability of accidental collision between an individual satellite and known resident space objects (RSOs) during that satellite's orbital lifetime. DAS does not calculate the risk of intra-system collisions. It also does not forecast expected growth in debris flux from future intra- and inter-system collisions. In order to assess the risk presented by a multi-satellite constellation, the individual contributions must be combined.

The probability of an individual LEO satellite being hit by an intact structure or large debris object (> 10 cm) during its orbital lifetime is approximated by:

$$P = F \times A \times T$$

where

F is the weighted cross-sectional area orbital debris environment flux (number/m^2)

A is the average satellite cross-sectional area (m^2)

T is the orbital lifetime in years.

The weighted cross-sectional area flux is derived by evaluating the amount of time the satellite spends in different altitudes during its orbital lifetime. This value is determined by DAS given the initial orbit, area-to-mass ratio, and the launch date of the satellite. Station keeping, disposal orbits, and passive decay are modeled by summing the probability of collision evaluated separately for various altitudes.

The following table was prepared using DAS 3.1.1 with the latest, 16 December 2020, solar flux table and a January 2021 launch date. It compares the average probability of per satellite large object collisions, the expected number of collisions per constellation over satellite lifetime, and the mean time between collisions for various SpaceX constellations, and for the Viasat LEO constellation. It is seen that SpaceX's system has become more dangerous after

3 NASA Technical Standard, Process for Limiting Orbital Debris, NASA-STD-8719.14B, 2019-04-25.

4 https://software.nasa.gov/software/MSC-26690-1.

each constellation modification, from an average of one collision every 5.1 years to one every 3.7 years. Viasat's LEO is seen to be over 40 times safer, with an average of one collision every 190 years.

Table 4 – Average Probability of Per Satellite Large Object Collisions, Expected Number of Collisions Per Constellation over Satellite Lifetime, and Mean Time Between Collisions

	Average Probability	Expected Collisions	Mean Time Between Collisions
SpaceX 2016	2.22E-04	0.98	5.1 years
SpaceX 2018	2.67E-04	1.18	4.3 years
SpaceX 2020 (pending)	3.07E-04	1.35	3.7 years
Viasat LEO 288	1.37E-04	0.04	190 years

The following tables show the expected number of large objects collisions for the SpaceX constellations as they have evolved over time, and for the Viasat LEO constellation. For all constellations, station keeping, 300-km post mission disposal orbit perigee, and January 2021 launch date are assumed.[5] The Starlink satellites are modeled as having 5-year mission life, 260-kg mass, and 0.0974 m^2/kg area-to-mass ratio. The Viasat satellites are modeled as having 7.5-years mission life, 300-kg mass, and 0.1-m^2/kg area-to-mass ratio. The DAS probabilities are per satellite.

Table 5 – SpaceX 2016 Constellation: Expected Number of Large Object Collisions

Number of Satellites	Inclination	Altitude	DAS Probability	Collisions
1600	53°	1150 km	1.89E-04	0.30
1600	53.8°	1110 km	2.64E-04	0.42
400	74°	1130 km	2.80E-04	0.11
375	81°	1275 km	2.15E-04	0.08
450	70°	1325 km	1.50E-04	0.07
			TOTAL	0.98

Table 6 – SpaceX 2018 Constellation: Expected Number of Large Object Collisions

Number of Satellites	Inclination	Altitude	DAS Probability	Collisions
1584	53°	550 km	2.74E-04	0.43
1600	53.8°	1110 km	2.64E-04	0.42
400	74°	1130 km	3.88E-04	0.16
375	81°	1275 km	2.15E-04	0.08
450	70°	1325 km	1.89E-04	0.08
			TOTAL	1.18

5 Same start date is used for comparative purposes, to ensure consistency in results.

Table 7 – SpaceX 2020 (proposed) Constellation: Expected Number of Large Object Collisions

Number of Satellites	Inclination	Altitude	DAS Probability	Collisions
1584	53°	550 km	2.74E-04	0.43
1584	53.2°	540 km	2.59E-04	0.41
720	70°	570 km	3.88E-04	0.28
520	97.6°	560 km	4.41E-04	0.23
			TOTAL	1.35

Table 8 – Viasat LEO (proposed) Constellation: Expected Number of Large Object Collisions

Number of Satellites	Inclination	Altitude	DAS Probability	Collisions
288	45°	1270 km	1.37E-04	0.04

Annex B
Application of Kinetic Theory of Gases to Estimating LEO Constellation Self Collision Rates

The kinetic theory of gases has long been used to estimate satellite collision rates, see references below. This technique can also be applied to estimating the intra-system (self) collision rate of a LEO mega constellation. The collision rate (collisions per year) is estimated by:

$$F = C \times N \times D \times v \times \sigma$$

where

C = 31,536,000 is the number of seconds in a year

N is the number of satellites in the shell

$D = N/V$ is the density of satellites in the shell (km^{-3})

- $V = \pi/3 \times (R_2^3 - R_1^3) \times (4 - 2(2 + \sin i)(1 - \sin i)^2)$ is the shell volume (km^3)
  - R_1 and R_2 are the min and max orbit radii, respectively, (km)
  - i is the orbit inclination

$v = \sqrt{2\mu/R}$ is the average relative velocity of the satellites (km/s)

- $\mu = 398{,}600$ (km^3/s^2) is the Earth's gravitational parameter
- $R = (R_1 + R_2)/2$ is the average orbital radius (km)

$\sigma = 4\pi r^2$ is the collision cross-section (km^2)

- r is the satellite's hard body radius (km)

The following tables show the results of applying this estimate to the various SpaceX constellations, and to the Viasat LEO constellation.

Table 9 – SpaceX 2016 Constellation Estimated Intra-System Collision Rate

Number of Satellites	Inclination	Min Shell Altitude	Max Shell Altitude	Hard Body Radius	Collision Rate
1600	53°	1120 km	1180 km	4.5 m	5.2/year
1600	53.8°	1080 km	1140 km	4.5 m	5.3/year
400	74°	1100 km	1160 km	4.5 m	0.3/year
375	81°	1245 km	1305 km	4.5 m	0.3/year
450	70°	1295 km	1355 km	4.5 m	0.4/year
				TOTAL	11.5/year

Table 10 – SpaceX 2018 Constellation Estimated Intra-System Collision Rate

Number of Satellites	Inclination	Min Shell Altitude	Max Shell Altitude	Hard Body Radius	Collision Rate
1584	53°	520 km	580 km	4.5 m	6.3/year
1600	53.8°	1080 km	1140 km	4.5 m	5.3/year
400	74°	1100 km	1160 km	4.5 m	0.3/year
375	81°	1245 km	1305 km	4.5 m	0.3/year
450	70°	1295 km	1355 km	4.5 m	0.4/year
				TOTAL	12.6/year

Table 11 – SpaceX 2020 (proposed) Constellation Estimated Intra-System Collision Rate

Number of Satellites	Inclination	Min Shell Altitude	Max Shell Altitude	Hard Body Radius	Collision Rate
1584	53°	520 km	580 km	4.5 m	6.3/year
1584	53.2°	510 km	570 km	4.5 m	6.3/year
720	70°	540 km	600 km	4.5 m	1.2/year
520	97.6°	530 km	590 km	4.5 m	0.6/year
				TOTAL	14.5/year

Table 12 – Viasat LEO (proposed) Constellation

Number of Satellites	Inclination	Min Shell Altitude	Max Shell Altitude	Hard Body Radius	Collision Rate
288	45°	1270 km	1330 km	3 m	0.077/year

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Annex C
Use of NEAT to Estimate Collisions Resulting from Low Probability Conjunction Alerts

The Number of Encounters Assessment Tool (NEAT) was developed by AGI and assesses collision risk by adjusting key constellation parameters to estimate conjunction warnings, maneuvers, and collisions.[6] **Table 13** compares the estimated yearly warnings, avoidance maneuvers, and collisions not avoided with mean-time-between-collisions (MTBC). It was computed using NEAT with the 19,697-current catalog of resident space objects and does not account for the significant growth that will be seen as proposed mega constellations deploy.

The warnings and maneuver thresholds were set to 3 km and 1 km, respectively. The number of "collisions not avoided" is calculated assuming that all avoidance maneuvers are successful, and that the probability of collision for the warnings that do not result in maneuvers is 10^{-5} (0.00001).

The numbers of warnings, maneuvers, and collisions-not-avoided increase with each modification. In all cases, they are significantly higher than those for the Viasat constellation.

Table 13 – Comparison of Estimated Yearly Warnings, Avoidance Maneuvers, Collisions not Avoided, and MTBC

	Warnings	Maneuvers	Collisions Not Avoided	MTBC
SpaceX 2016	216,602	24,067	1.9/year	0.52 years
SpaceX 2018	1,019,029	113,226	9.1/year	0.11 years
SpaceX 2020 (pending)	1,223,832	135,981	10.9/year	0.09 years
Viasat LEO 288 (pending)	7	1,900	0.15/year	6.58 years

The following tables show the estimated yearly warnings and avoidance maneuvers for each of the constellations considered.

Table 14 – SpaceX 2016 Estimated Yearly Warnings and Avoidance Maneuvers

Number of Satellites	Inclination	Altitude	Warnings	Maneuvers
1600	53	1150	66,700	7,411
1600	53.8	1110	82,470	9,163
400	74	1130	26,655	2,962
375	81	1275	29,067	3,230
450	70	1325	11,710	1,301
		TOTAL	216,602	24,067

6 *See* https://www.agi.com/missions/space-situational-awareness/what-s-the-number-of-encounters-assessment-tool-it.

Table 15 – SpaceX 2018 Estimated Yearly Warnings and Avoidance Maneuvers

Number of Satellites	Inclination	Altitude	Warnings	Maneuvers
1584	53	550	869,127	96,570
1600	53.8	1110	82,470	9,163
400	74	1130	26,655	2,962
375	81	1275	29,067	3,230
450	70	1325	11,710	1,301
		TOTAL	1,019,029	113,226

Table 16 – SpaceX 2020 Estimated Yearly Warnings and Avoidance Maneuvers

Number of Satellites	Inclination	Altitude	Warnings	Maneuvers
1584	53	550	869,127	96,570
1584	53.2	540	169,616	18,846
720	70	570	107,070	11,897
520	97.6	560	78,019	8,668
		TOTAL	1,223,832	135,981

Table 17 – Viasat LEO (proposed) Estimated Yearly Warnings and Avoidance Maneuvers

Number of Satellites	Inclination	Altitude	Warnings	Maneuvers
288	45	1300	17,100	1,900

DECLARATION OF MARK A. STURZA

I, Mark A. Sturza, hereby make the following declarations under penalty of perjury:

1. I am President of 3C Systems Company, which has acted as consultant to Viasat, Inc. (“Viasat”) regarding the matters addressed in the foregoing letter.

2. I prepared the engineering information submitted in the foregoing letter and otherwise have reviewed its substance, which is complete and accurate to the best of my knowledge, information and belief.

/s/

Mark A. Sturza
President
3C Systems Company

January 15, 2021