Risk of Increased Fragmentation Events due to Low Altitude Large Constellation Spacecraft

A. Vavrin[(1)], A. Manis[(2)], D. Gates[(3)], M. Matney[(4)]

[(1)] GeoControl Systems – Jacobs JETS Contract, NASA Johnson Space Center, Mail Code XI5-9E, 2101 NASA Parkway, Houston, TX 77058, USA
[(2)] HX5 – Jacobs JETS Contract, NASA Johnson Space Center, Mail Code XI5-9E, 2101 NASA Parkway, Houston, TX 77058, USA
[(3)] Jacobs Technology, NASA Johnson Space Center, Mail Code XI5-9E, 2101 NASA Parkway, Houston, TX 77058, USA
[(4)] NASA Johnson Space Center, Mail Code XI5-9E, 2101 NASA Parkway, Houston, TX 77058, USA

ABSTRACT

Orbital debris experts and industry leaders are concerned about the added hazard that thousands of additional spacecraft would have on the future orbital debris environment. Large constellations proposals plan to deploy spacecraft at altitudes from 1100 km to 1300 km, where fragmentation debris can take thousands of years or longer to decay naturally, while other proposals include deploying spacecraft at station-keeping altitudes from 300 km to 600 km. Although these lower altitude spacecraft are compliant with the 25-year rule, there is still an increased risk of accidental explosions generating high velocity fragments that could damage international spacecraft assets.

The NASA Orbital Debris Program Office (ODPO) has conducted several parametric studies that examine the potential negative environmental impacts of large constellation deployments [1, 2]. This study addresses the lower altitude constellations and the potential risk that they impose on the future environment during mission operations. The projected future environment is generated as the average of 100 LEGEND Monte Carlo (MC) simulation runs while adjusting parameters such as average probability of explosion and operational lifetime per constellation. Results of the effect of accidental explosions of large constellation spacecraft on the environment below 600 km altitude are analyzed.

1 INTRODUCTION

Several commercial companies have commenced development and deployment of telecommunications constellations consisting of hundreds to thousands of 100-to-300-kg class spacecraft in low Earth orbit (LEO, the region below 2000 km altitude). From the large number of spacecraft and amount of mass involved to support large constellations (LCs), the frequent deployment, operations, de-orbit, and replenishment of the proposed LCs could significantly contribute to the existing orbital debris problem. Because of the weak atmospheric drag above 1000 km altitude, defunct spacecraft in that region can have orbital lifetimes of thousands of years or longer. These defunct spacecraft pose a danger to the operations of LCs and more importantly, are a long-term threat to the LEO environment; defunct spacecraft can and will collide with other debris over time, increasing the potential of generating more debris that triggers a collision cascade effect in the region. To mitigate risk at higher altitudes, some companies have elected to move their constellation to lower altitudes in LEO to ensure 100% compliance with the so-called 25-year rule [3].

The NASA Orbital Debris Program Office (ODPO) conducted a series of simulations using the LEO to GEO Environment Debris (LEGEND) [4, 5] model to investigate the long-term effects of adding thousands of large constellation spacecraft to the environment. Previous parametric studies on the effect of LCs on the LEO environment focused on post-mission disposal (PMD) reliability and limiting accidental explosion probability (P_{exp}) of proposed LC spacecraft, from three separate constellations, at mission altitudes above 1000 km [1, 2]. Based on the results of that study, recommendations were given to limit the probability of accidental explosions of the LC spacecraft during mission operations to less than 0.001, which is consistent with the NASA orbital debris requirement to limit accidental explosions [6]. Once the accidental explosion probability is limited to 0.001, the debris population increase is primarily driven by the 90% PMD success rate of the LC. If the LC spacecraft can achieve 99% PMD reliability and 0.001 accidental explosion probabilities, then their contribution to the future debris environment appears to be limited. Another recent study explored additional scenarios [7] by assuming that the post-mission disposal rates and explosion probabilities of LC spacecraft vary with time, representative of improvements to spacecraft systems and operations after initial learning periods. Results indicate different effects from time-varying PMD rates and explosion probabilities, particularly a difference in the overall effect of delaying improvements to spacecraft systems and/or operations to achieve either a target PMD rate or explosion probability after one or two replenishment cycles. Allowing a learning period for the first set of spacecraft deployed could have a profound, negative effect on the future space environment. Therefore, it is critical that LC spacecraft achieve both a high rate of PMD reliability as well as a low probability of explosion early in the constellation lifetime.

The objective of the parametric study considered here is to quantify the potential negative effects to the LEO environment caused by debris generation from LC explosions over the constellation lifetime. The large constellation introduced in each scenario is based on proposed large constellations below 600 km and their influence on LEO-crossing objects (i.e., effective number of 10 cm or larger objects crossing the LEO region, where the effective number is defined as the fractional time per orbital period that an object resides at 200 km to 2000 km altitude range). Due to the low operational altitudes, a PMD maneuver is not necessary since these LC spacecraft are naturally compliant with the 25-year rule. Although the long-term influence of these low altitude LC spacecraft on the environment is minimal, there is still a risk of accidental explosions that could take place during the constellation lifetime that should not be ignored. Since spacecraft in the same LC are likely to share similar, if not identical, designs and fabrication processes, a flaw leading to explosions could potentially exist in many spacecraft and might not be identified until years after launch or operations in orbit. Spacecraft should demonstrate that there is no credible failure mode for accidental explosion. If such credible failure modes do exist, then design or operational procedures will limit the probability of occurrence of such failure modes [8]. Therefore, it is important to assess the effect that the accidental explosion of constellation objects has on the future debris environment.

Section 2 describes the parametric study and the configuration of multiple scenarios used in the study with a focus on sensitivity of accidental explosion probability of 10-year and 20-year constellation lifetimes, respectively. Section 3 focuses on the increase in the overall breakup events in the future LEO environment. Section 4 details the effect of LC explosion fragments on the projected LEO environment. The paper concludes with summary and conclusions in section 5.

2 SETUP OF PARAMETRIC STUDY

Table 1. Setup Configuration for 1 Large Constellation. Varying parameters are listed in bold.

Description	**Value**
Start year of initial LC spacecraft launches	2020
Mass, beginning of mission, kg	225 (± 1%)
Mission duration, years	5
Mission altitude, km	340 (± 5) and 550 (± 5)
Spacecraft per monthly launch	110
Total operational spacecraft	6600
Start year of replenishment phase	2025
Explosions allowed through mission ops	Yes
Collision avoidance through mission ops	Yes
Constellation Lifetime, years	**10, 20**
Probability of Explosion over Mission Duration, P_{exp}	**0.01, 0.001, 0.0001, 0.0**

Table 1 shows the details on how the large constellation is configured for this study. All LC scenarios assume that, in addition to the background population, one LC operates at two different altitudes – 340 km and 550 km. The average mass of an individual spacecraft is 225 kg. To avoid assigning all spacecraft the same altitude and mass and to ensure a unique area-to-mass ratio per LC spacecraft, variability in altitude and mass was added to each LC spacecraft in the simulation (± 5 km for mission altitude, ± 1% for mass). After each spacecraft is deployed, it operates for the 5-year duration of its mission, and then discontinues station-keeping operations at the end of mission. A new spacecraft then replaces the retired one. This study assumes that there are no launch and/or deployment failures of any of the LC spacecraft in the future environment.

Furthermore, it is assumed that conjunction assessments and collision avoidance maneuvers are conducted for all LC spacecraft that have successful deployment and operations through final reentry. Each LC has two phases of deployment: initial and replenishment. During the initial phase, which starts in 2020 and lasts for 5 years, the large constellation reaches full deployment of its spacecraft. The replenishment phase begins in 2025, where spacecraft are constantly replenished until the end of constellation operations (i.e., 10 years or 20 years). The objective of the replenishment phase is to maintain 6600 spacecraft in mission operational orbits through regularly scheduled launch traffic of LC spacecraft. Spacecraft are launched on the first day of each month during both mission phases. The scheduled launch traffic characteristics for each LC spacecraft (orbital elements, mass, launch date, etc.) remain consistent for each scenario.

Description of the background population is as follows. The historical period covers launches through the end of 2017. Starting in 2018, the environment is projected 200 years into the future through the year 2217. The background future launch traffic is a repeat of the launches over the last 8 years of the historical space activities (2010-2017). For the background population, the PMD success rate of spacecraft and rocket bodies is set to 90%. Upper stages and spacecraft are assumed to explode in the future with accidental explosion probabilities derived from historical explosion events and collisions are assessed statistically using LEGEND's "cube" model [9].

3 INCREASE IN BREAKUP EVENTS DURING LARGE CONSTELLATION SPACECRAFT MISSION OPERATIONS

Since 1957 and as of July 2018, 242 satellites are believed to have broken up where the primary causes of satellite breakups are propulsion-related events and deliberate actions [10]. By looking at payload-only, non-deliberate breakups at an altitude less than 600 km, the number of known fragmentation events is reduced to 25 (about 10% of all known historical breakups). Applying these specific criteria to the historical record over the past 20 years (1998 – 2017) further reduces the number of breakups to 5 (about 2%). Nonetheless, this number is expected to increase substantially if the probability of accidental explosion for LC spacecraft is left unchecked.

Table 2. Analysis of LC breakup events in LEO during initial and replenishment phases, 10-year constellation lifetime

P_{exp}	Additional breakup events in LEO, from LC spacecraft	Average breakups per launch of LC spacecraft
0.0001	2.1	0.011
0.001	20.2	0.112
0.01	202.9	1.127

The cumulative number of LC breakup events and the cumulative average number per total of LC launches, through 5 years of initial launches and 10 years of replenishment, is shown in Table 2. As predicted, an increase in the explosion probability yields an increase in the number of LC-related breakup events, by approximately a factor of 10 for each factor of 10 increase in the explosion probability. The initial and replenishment phases comprise a total of 180 launches (15 years, 12 launches per year). When P_{exp}=0.0001 and P_{exp}=0.001, the number of expected LC breakup events per LC launch is 0.011 (about one in 100 launches, or one every 8 years) and 0.112 (about one in 9 launches, or one every 9 months), respectively. The worst case (P_{exp}=0.01 over 5 years) yields 202.9 more breakups than the baseline case (i.e., where LC spacecraft are not included in the environment), an average of one breakup every monthly launch.

Table 3. Analysis of LC breakup events in LEO during initial and replenishment phases, 20-year constellation lifetime

P_{exp}	Additional breakup events in LEO, from LC spacecraft	Average breakups per launch of LC spacecraft
0.0001	4.1	0.013
0.001	38.0	0.126
0.01	381.6	1.272

In Table 3, the cumulative number of LC breakup events through all mission phases is shown, as well as the cumulative average breakups per launch of LC spacecraft. A total of 300 launches occur during the initial and replenishment phases (initial 5 years plus 20 years replenishment at 12 launches per year). When P_{exp}=0.0001 and P_{exp}=0.001, the number of expected LC breakup events per LC launch is 0.013 (about one in 100 launches, or one every 8 years) and 0.126 (about one in 8 launches, or one every 8 months), respectively. The worst case (P_{exp}=0.01 over 5 years) yields 381.6 more breakups than the baseline case (i.e., where LC spacecraft are not included in the environment), an average of one breakup every monthly launch. As compared to the 10-year replenishment case (Table *2*), the cumulative number of LC breakup events is approximately doubled for each explosion probability scenario, but since the constellation lifetime is also doubled, the averge number of breakup events per monthly launch is approximately the same. As the accidental explosion probability becomes greater than 0.001, the number of breakup events due to LC spacecraft escalates for both the 10-year and 20-year constellation lifetime.

4 PERCENTAGE OF LC EXPLOSION FRAGMENTS, > 10 CM, IN FUTURE LEO ENVIRONMENT

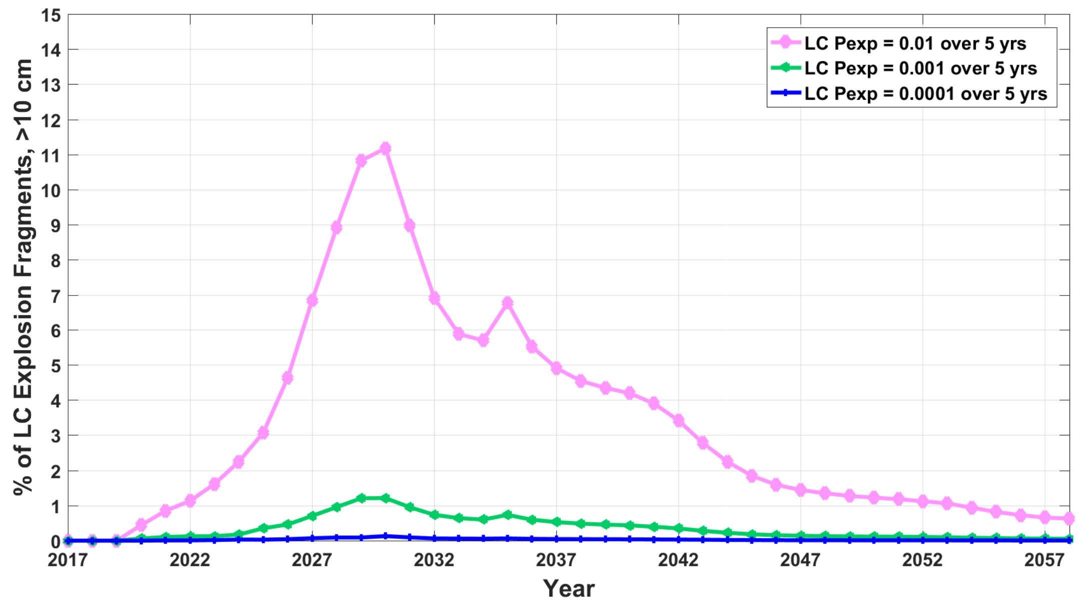

Fig. 1. Percentage of LC Explosion Fragments (>10 cm) in future LEO environment, 10-year constellation lifetime.

Fig. *1* shows the percentage of the total effective number of objects (i.e., background population with LC-related objects >10 cm) that reside in the projected future LEO environment, which are LC explosion fragments for the 10-year constellation lifetime case. The accidental probability of explosion of LC spacecraft over the 5-year mission lifetime is set to 0.0001, 0.001, and 0.01, respectively, for the three scenarios. Results show that a debris population composed of LC explosion fragments are constantly created (from new breakups) and removed (via reentry) during the initial and replenishment phases of the constellation. This population noticeably decreases once the replenishment phase of the large constellation ends. As P_{exp} approaches 0.01, the total effective number of objects increases due to the increased number of LC breakup events, where 11% of the LEO population in 2030 is composed of LC explosion fragments. Another reason for this proliferation of fragments is a solar minimum in the projected solar cycle where objects tend to stay in orbit longer due to lack of atmospheric drag. When the accidental explosion probabilities of the LC spacecraft are reduced to 0.001 or less, the percentage of LC explosion fragments barely rises above 1% of the total population.

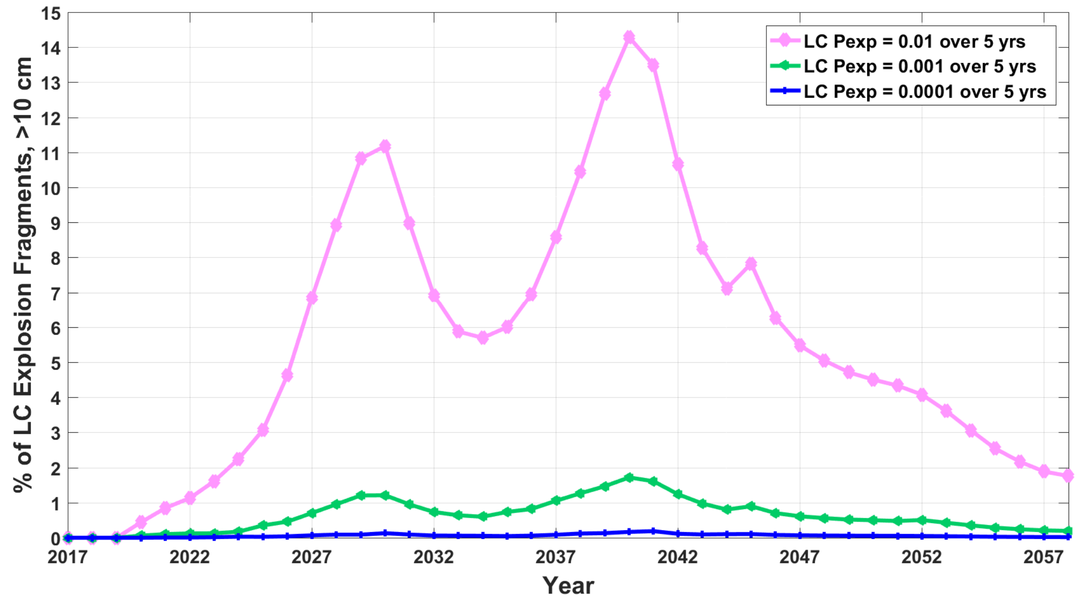

Fig. 2. Percentage of LC Explosion Fragments (>10 cm) in future LEO environment, 20-year constellation lifetime.

Fig. *2* shows the percentage of the total effective number of objects composed of explosion fragments from LC spacecraft. The LC launch traffic cycle used in these scenarios is extended to 20 years. For the P_{exp}=0.01 case, the percentage of LC explosion fragments reaches 11% of the LEO population in 2030, similar to the 10-year constellation lifetime case, and a second maximum of 14% of the LEO population in 2040. As shown in the scenarios from the 10-year constellation lifetime, the percentage of LC explosion fragments noticeably decreases once the replenishment phase of the large constellation ends.

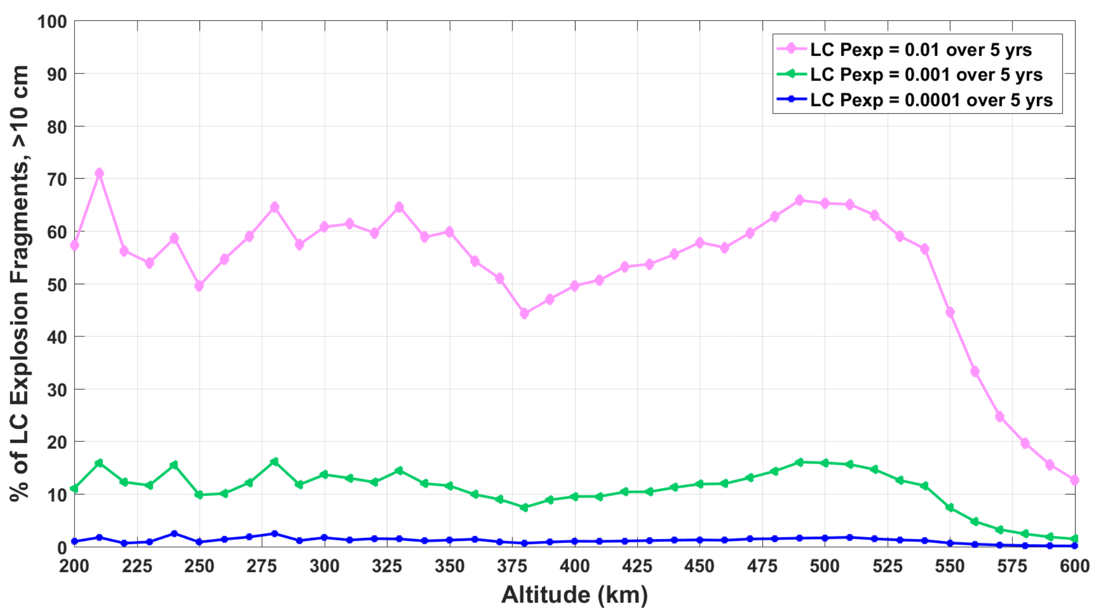

Fig. 3. Percentage of LC Explosion Fragments, altitude range 200 km to 600 km,
10-year constellation lifetime, at end of year 2034.

The effects of LC explosion fragments on LEO altitudes at the end of the constellation lifetime is also explored. Fig. *3* shows the percentage of the total effective number of objects that are composed of LC explosion fragments at the altitude range of 200 km to 600 km at the end of the 10-year constellation lifetime (i.e., in 2034). Results from three scenarios, where P_{exp} is set to 0.0001, 0.001, and 0.01, respectively, show that these fragments are not a major contributor to the environment for altitudes above 550 km (i.e., the LC mission altitude). However, this population of fragmentation debris is relatively consistent across all lower altitudes (< 550 km) and increases as the accidental explosion probabilities of the LC spacecraft are increased. For the P_{exp}=0.01 case, the percentage hovers between 45% to 70% of the total effective number of objects. Thus, while these fragments may have relatively short orbital lifetimes, they dominate the environment at altitudes between 200 km to 600 km at the end of the constellation lifetime, which could increase the risk to operational spacecraft in these altitudes. Reducing P_{exp} to 0.001 lowers this proportion to 10% to 15%, and less than 2% when P_{exp}=0.0001.

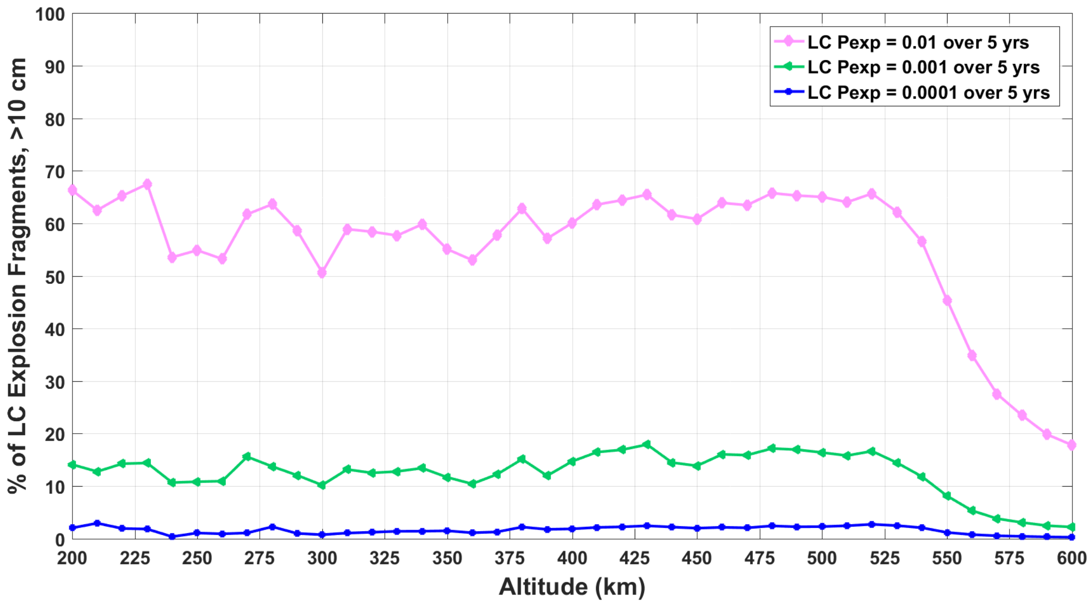

Fig. 4. Percentage of LC Explosion Fragments, altitude range 200 km to 600 km,
20-year constellation lifetime, at end of year 2044.

These trends are also present when the constellation lifetime is extended to 20 years, as shown in Fig. 4. For the P_{exp}=0.01 case, the percentage hovers near 50% to 70% of the total effective number of objects, which again means they comprise a significant portion of the population at altitudes between 200 km to 600 km at the end of the constellation lifetime. Reducing P_{exp} to 0.001 lowers this proportion to 10% to 20%, and to less than 4% when P_{exp}=0.0001.

5 SUMMARY

This study analyzed the effects of fragmentation events of large constellation spacecraft on the future LEO environment below 600 km altitude. When assessing the effects of the long-term environment, all scenarios in this study meet NASA mitigation standards for limiting orbital debris creation in the long-term projected environment (i.e., compliance with the 25-year rule).

Simulations show that a debris population of LC explosion fragments is continually replenished with each subsequent breakup of an LC spacecraft at mission altitudes for the duration of the constellation lifetime. This can have a significant effect on the environment during constellation lifetime if accidental explosion probability is not constrained. When constellation operations conclude after a 10-year or 20-year lifetime, the LC explosion fragments dominate the environment at altitudes between 200 km to 600 km when the probability of explosion is greater than 0.001. Although fragmentation debris reenter quickly after creation at the low altitudes considered here, the additional fragments in these low altitudes increase the risk of catastrophic collisions for other spacecraft assets.

With a probability of explosion of 0.001 and lower, the effect on the environment at these low altitudes appears to be minimized.

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