INTERACTIONS BETWEEN DEBRIS MITIGATION AND SPACE TRAFFIC SAFETY IN THE PRESENCE OF LARGE CONSTELLATIONS

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ABSTRACT

Recent projections of future space activity anticipate significant increases in the numbers of active satellites which include large constellations from hundreds to tens-of-thousands of satellites. To construct an effective set of best practices, standards, or regulations for safe space operations, it is necessary to quantitatively understand how the different, sometimes conflicting, aspects of space operations interact both positively and negatively. Post-mission disposal of satellites reduces debris-generating collision risk, but stricter disposal requirements can also increase conjunction frequencies for satellites in lower orbits.

This paper considers the interaction between debris mitigation approaches and the associated conjunction environment. The study examines a range of future launch traffic scenarios including different numbers, configurations, and locations of large constellations. Several techniques for, and levels of, post-mission disposal are modelled to examine the resulting conjunction frequencies for operating spacecraft.

1 INTRODUCTION

Recent projections of future space activity anticipate significant increases in the numbers of active satellites. This is substantiated by proposals for large constellations that can include from hundreds to tens-of-thousands of satellites. Several of these constellations are in various stages of deployment and operation. Many studies have been conducted considering the implications of this large increase in space activity on the orbital debris environment and considered needs for mitigation practices to control the growth of that environment. Other studies have considered the effect of operating large constellations on conjunction frequency and collision avoidance, both for satellites on orbit and for launches that will pass through or into the regions of space occupied by these constellations.

The Aerospace Corporation has started an effort to understand the larger picture and consider the interplay of the many aspects of safe space operations. In order to construct an effective set of best practices, standards, or regulations for safe space operations, it is necessary to quantitatively understand how the different, sometimes conflicting, aspects of space operations interact both positively and negatively. Post-mission disposal of satellites in LEO reduces their time in orbit significantly, reducing debris-generating collision risk, but stricter disposal requirements can also increase conjunction frequencies for satellites in lower orbits. Different lengths of post-mission disposal, different disposal processes, and different physical distributions of constellations may all affect the operating environment around and below them. Post-mission disposal practices may be effective for limiting the long-term growth of the debris environment but may have short-term implications for operations.

This paper will consider the interaction between debris mitigation approaches, the evolution of the debris environment and the associated conjunction environment. The study examines a range of future launch traffic scenarios including different numbers, configurations, and locations of large constellations. Several techniques for, and levels of, post-mission disposal are modelled to examine the resulting future debris environments and associated conjunction frequencies for operating spacecraft. The conjunction frequency characteristics under different future tracking uncertainty assumptions will also be considered.

Study results will be examined in the context of balancing debris mitigation and conjunction frequency considerations and will consider implications of

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conflicting effects.

2 AEROSPACE DEBRIS ENVIRONMENT PROJECTION TOOL (ADEPT)

The Aerospace Debris Environment Projection Tool (ADEPT) simulation process generates representations of the future orbital population. The model includes orbit trajectories and sizes for a complete set of Earth orbital objects. Early versions of ADEPT are described in 1 and 3. More recent enhancements and a detailed description of the of ADEPT are described in 1 and 4. In brief:

1. The ADEPT model starts with an initial population model (IPM) that includes all the known catalog objects and modelled objects that represent unknown and subtrackable (between 1 cm and 10 cm) objects on orbit.
2. A future launch model (FLM) that includes a Future Constellation Model (FCM) and extends out 200 years is added.
3. Ephemeris for this population is generated by long-term propagation using the mean-element code MEANPROP (Draper Semi-Analytic Orbit Propagator 5).
4. Future random collisions are generated using an orbit trace crossing method (OTC).
5. The fragmentation modelling code IMPACT 6 is used to generate fragments from explosions and collisions.
6. Fragments are fed-back into the process at step (3) to generate multiple generations of feedback collisions and fragments, as needed.

Down sampling, as described in 4 is used to keep the overall count of object- to process to a computationally tractable number while maintaining population distributions. The post-mission disposal failure approach is briefly covered in 1. The processes are depicted in Figure 1 and Figure 2.

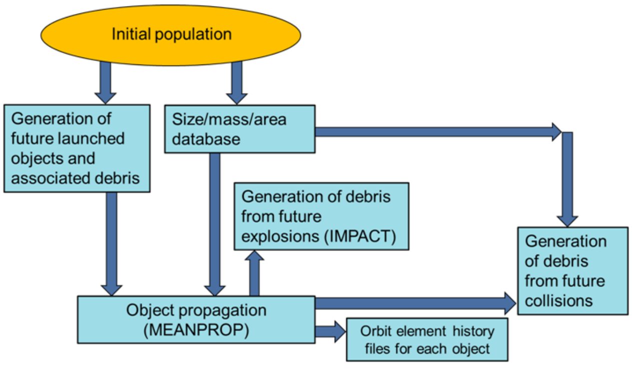

Figure 1. ADEPT Population Generation Process

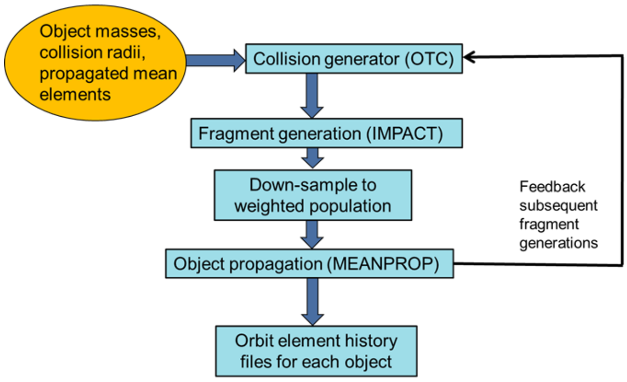

Figure 2. ADEPT Process for Generating Debris from Future Collisions

3 STUDY INITIAL CONDITIONS AND MODIFIED ANALYSIS

The initial population model (IPM) for the simulation consisted of several sub-populations. The current public catalogue (dated Dec 21, 2020) provided the fundamental background of tracked objects. Some of the current catalogue objects are members of existing constellations. For the purposes of this simulation, two generic constellations were to be examined so the currently existing Starlink and OneWeb constellations' satellites were removed from the IPM to avoid conflicts with the simulated constellations. The remaining existing constellations (Iridium, Globalstar, Orbcomm) were retained in the IPM. The IPM was enhanced with additional objects to reflect the reported number of objects of trackable size. The same orbit element distribution as observed in the current catalogue was employed for these unknown objects resulting in approximately a 50% increase in the overall number of initial objects. Two populations were also included in the IPM to simulate the 1-10 cm population. The first represented the general small object population created from historical explosions and collisions and, as with the unknowns, followed the general distribution of the public catalogue objects. The other represented the residue from the Fengyun 1C event.

A future launch model (FLM) was employed to add satellites and rocket bodies to the population as the simulation time progressed. The FLM consisted of replenishing the Iridium, Globalstar, and Orbcomm constellations on a continuous basis with operational lifetimes of 12 years. Also, the non-constellation background in LEO was reproduced continuously assuming a 5-year satellite operational timeline. After operations (satellites) or deployment (rocket bodies), the objects were moved to either a 5-year disposal orbit or a 25-year disposal orbit. When failures occurred, the object was left on an orbit randomly distributed between where they began and where the disposal orbit lay. In addition, each rocket body in the non-constellation background was assumed to release 30 CubeSats, which were allowed to drift to decay from whatever orbit they were released from.

Two generic representations of proposed large constellations were included in the populations modelled. The orbital characteristics of the constellations can be seen in Table 1 and physical characteristics of the constellation satellites are shown in Table 2. One constellation is in a range of lower orbits from 650 km altitude and below. This constellation is referred to as LO LEO. The second constellation, referred to as HI LEO, is in an altitude range from 1100 to 1400 km. The constellations are designed in shells at evenly spaced altitudes within their ranges where each shell within a constellation has similar characteristics. The configuration of the constellations allows the construction of several effective constellations by including or excluding different constellation shells for different space traffic scenarios.

Table 1: LLC Orbit Parameters

Const	Total Sats	Alt. (km)	Inc (deg)	Planes	Sats per Plane
HI LEO					
A	5000	1100	73	50	100
B	5000	1200	73	50	100
C	5000	1300	73	50	100
D	5000	1400	73	50	100
LO LEO					
A	5000	350	39	50	100
B	5000	400	39	50	100
C	5000	450	39	50	100
D	5000	500	39	50	100
E	5000	550	39	50	100
F	5000	600	39	50	100
G	5000	650	39	50	100

Throughout the rest of the paper the constellation shells will be referred to as “LO” or “HI” and include the shell letter per Table 1.

Table 2: LLC Satellite Physical Parameters

Const	Satellite Area (m^2)	Satellite Diameter (m)	Satellite Mass (kg)
HI LEO	3.17	3.37	147
LO LEO	15.45	5.96	268

Constellation satellites were given 5-year operational lifetimes. The constellations were continuously maintained with satellites that reached their operational lifetime limits being replaced by new satellites with new launches. When satellites reached then end of their lifetimes, they were placed in several options for disposal orbits with some satellites also having a “fail” option where they did not successfully dispose.

Three different post-mission disposal options were considered for the different populations in the model.

- 25-year disposal orbit lifetime (25-year rule)
- 5-year disposal orbit lifetime
- 2-yr low thrust deorbit

The 25-year disposal follows the standard 25-year rule as described in the Inter-Agency Space Debris Coordination Committee (IADC) Debris Mitigation Guidelines [7], and the USG Orbital Debris mitigation Standard Practices (ODMSP) [8]. Objects using this option were placed on near circular orbits with lifetimes of approximately 25 year at the end of their missions. Objects using the 5-year disposal were placed on similar disposal orbits but with an approximately 5-year orbital lifetime. Objects using the low thrust disposal option were placed on orbits, starting near their operational orbits, with a continuous thrust to lower their orbits to re-entry in approximately 2 years. The thrust was constrained to lie in the along-track direction and so slowly decreased the semi-major axis in a spiral without changing the orbital plane. For the HI LEO, this allowed for the re-entering satellites to experience the high numbers of objects residing in the background at 700-900 km. Table 3 shows which populations were allowed which disposal options. Only the two large constellations were allowed the low thrust option as few members of the other populations have that capability.

Table 3: Post-Mission Disposal Options

Const	2-year LT	5-year	25-year
CRC		X	X
nonCRC		X	X
HI LEO	X	X	X
LO LEO	X		

The populations examined included a range of options for post-mission disposal success rate. This rate included 60%, 70%, 80% and 90% success rates. For objects that failed in their post-mission disposal operations the object was left in the vicinity of its operational orbit.

For this study the analysis focused on the first 50 years after the simulation start time. This differs from the typical simulations times of 200 years used for orbital debris environment evolution simulations. Because the study was concerned with the operational environment a shorter time scale was used, but one that was sufficiently long for the constellations to reach a constituent sate with respect to satellites cycling though the full ranges of disposal states.

For this study an additional set of data was extracted from the model. The OTC process examines cases where the orbit traces of two objects cross (OTC events) and then determines a collision probability using a miss distance based on the sizes of the two objects as well as the orbital parameters of the two objects at the OTC events. For this analysis the same process was also used with a miss distance of 1 km to represent a conjunction between the two objects rather than a collision. This approach uses an extended analytical formulation of the probability to account for the possibility that the orbit traces may still be within the miss distance for more than one orbital revolution. The random variable underling the probability is the relative in-track position between the two objects, which is assumed to be uniformly distributed over 360 degrees. The algorithm then sums those probabilities over all the OTC events for a given pair of objects to get the mean number of close approaches over the simulation time frame. If the resulting value is < 0.1 it is approximately a probability. If it is > 0.1 it is passed through a Poisson distribution to get a probability. In this way a representation of the conjunction environment for a variety of different future traffic scenarios can be constructed.

4 LARGE CONSTELLATION IMPACT ON THE ENVIRONMENT

The existence of the large constellations has a noticeable effect on the orbital environment even over the 50 years considered in this study. Figure 3 shows the effect of one configuration of the large constellations on the overall population over the first 50 years. In the legend, "pmd060" refers to a 60% success rate of post-mission disposal, "pmd070" refers to a 70% success rate of post-mission disposal, and so on. Differences can be seen due to the different post-mission disposal success rates considered for a 25-year disposal option. In all cases there is a large increase in the total population of > 10 cm objects due to the presence of the constellations.

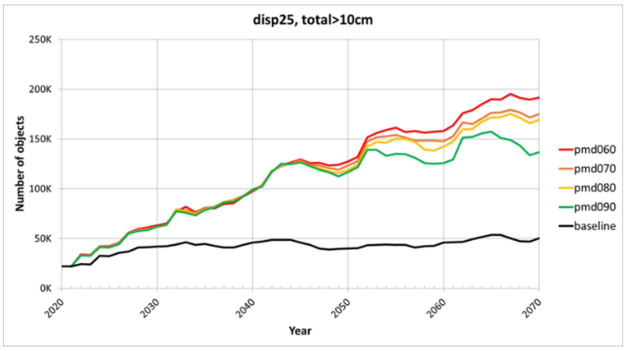

Figure 3. Number of > 10 cm Objects in Orbit Including LO-D and HI-A Large Constellations

The differences in population over 50 years due to the presence of the constellations can also be seen when considering a single post-mission disposal success rate and varying the type of disposal option used. This is shown in Fig. 2. In the legend, "disp25" indicates the use of a 25-year limit on orbital lifetime, "disp05" indicates the use of a 5-year limit on orbital lifetime, and "dispLT" indicates the use of low-thrust to re-enter within 2 years.

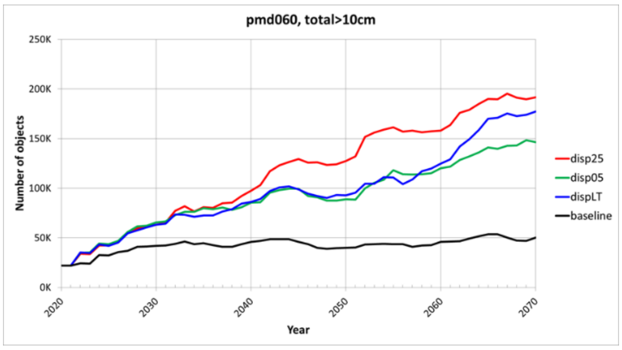

Figure 4. Number of > 10 cm Object in Orbit Including LO-D and HI-A Large Constellations

5 CONJUNCTION ENVIRONMENT RESULTS

The primary focus of this study is to consider the different conjunction environments encountered by components of the active and disposed satellite populations under a range of future traffic scenarios. Previous studies as in [9] have considered the effect of large constellations and tracking changes on conjunction frequencies. Here the goal is to consider the overall conjunction environment that is being generated. The main parameter considered is the average number of conjunctions (approaches within 1 km) per object per year. The 1 km distance was chosen as representative of a conjunction for which some effort would be expended by operators to examine the event more closely and possibly perform a collision avoidance manoeuvre. To calculate the average number of conjunctions the effective number of object years for the populations of interest in a given altitude bin were determined. The number of conjunctions involving the populations of interest were also determined and the number of conjunctions was divided by the object years. These average numbers of conjunctions per year provide insight into the relative conjunction environments that would be experienced by different subsets of the population for different space traffic scenarios. The figures that follow show the average number of conjunctions per satellite binned by altitude for 50 km or 100 km bins. In future work finer binning will be used to increase resolution of results. The numbers of conjunctions are plotted at the bottom of each bin. The altitude distributions provide additional insight into the nature of the conjunction environment being observed. The traffic scenario effects on the conjunction environment can then be compared to similar types of situations and their effects on the debris environment.

5.1 Effects of different constellation configurations

An initial examination was made of the effect of the constellations on the operational satellites that constitute the background population. Figure 5 shows the average conjunction rate per operational background satellite for the different LO LEO and HI LEO constellation shells. The "Baseline" curve represents the average number of conjunctions per year with neither the LO LEO nor HI LEO present.

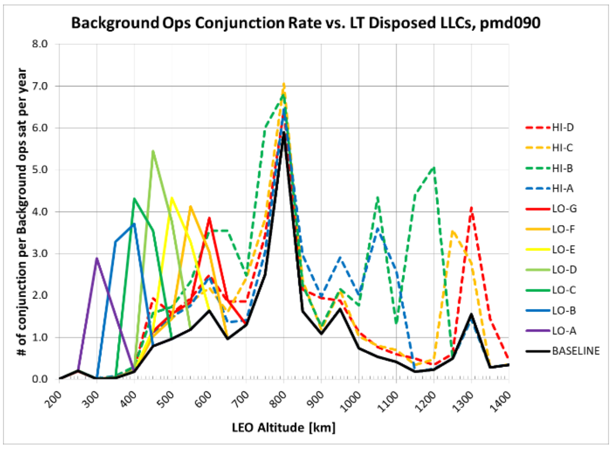

Figure 5. Background operational satellite conjunctions versus disposed HI and LO LEO configurations

Passage through the LO LEO shells can clearly be seen in the solid lines in Figure 5. The decreasing conjunction rates at altitudes below the initial disposal orbit altitudes are likely due to the increased rate at which background objects decay through the LO LEO shells at the lower altitudes.

The HI LEO dotted lines also show the effects of presence of background objects in the vicinity of the shells of the constellation. There is likely to be more sensitivity to the results for the HI LEO constellation because there is a smaller set of background objects passing through and interacting with the constellation shells at this higher altitude.

5.2 Low LEO constellations

The conjunction environment is different depending on which satellites are of interest with respect to the average number of conjunctions per year. In this series of plots the conjunction environment is examined from the perspective of the LO LEO constellation operational satellites. These satellites are generally below many other operational satellites and so will interact with them as these other satellites are disposed and decay through the LO LEO operational altitudes.

Figure 6 shows the conjunction rates for the 5-year disposal option for different post-mission disposal success rates. This case includes the HI-A shell along with the background satellites. The spike in the average number of conjunctions per year at the 550 km bin is likely due to the 5-year disposal altitude for the HI-A shell. It can be seen that the post-mission disposal success rate over most of the range has little effect on the conjunction rate.

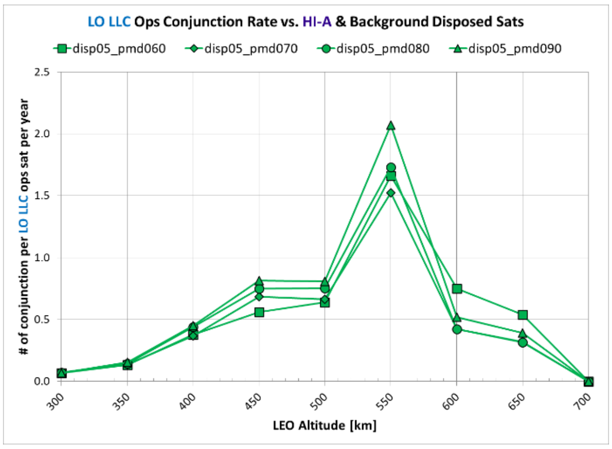

Figure 6. LO LEO (LO A-G) operational satellite conjunctions versus HI LEO (HI-ABCD) and background 5-year disposal

Figure 7 shows the average conjunction rate versus altitude for the three disposal options used by the HI LEO constellation. Again, the average conjunction rates include conjunctions with both the HI-A shell satellites and the background objects all with a 90% post-mission disposal success rate. The peaks in the curves for the 25-year and 5-year disposals correspond to the altitude bins where the disposed satellites are initially placed. Because of the increasing density of the atmosphere with decreasing altitude the disposed HI-A satellites tend to spend more of their time at the higher altitudes of their disposal. Several differences can be seen between the average number of conjunctions per year in the 25-year and 5-year disposal scenarios. The higher altitude of the peak for the 25-year disposal option is due to the high altitude of the initial near-circular disposal orbits. A peak in the 5-year scenario conjunction rates occurs at a lower altitude which also corresponds to the altitude of the initial near-circular disposal orbit. The magnitude and width of the peak in the 25-year disposal scenario is significantly larger than for the 5-year disposal scenario. This is likely due to the much longer time that the 25-year disposal objects spend in the altitude ranges at and slightly lower than the initial disposal orbit altitude. Again, this is caused by the increasing density of the atmosphere with decreasing altitude. In both cases the times over which the average number of conjunctions is calculated (5 years) are the same.

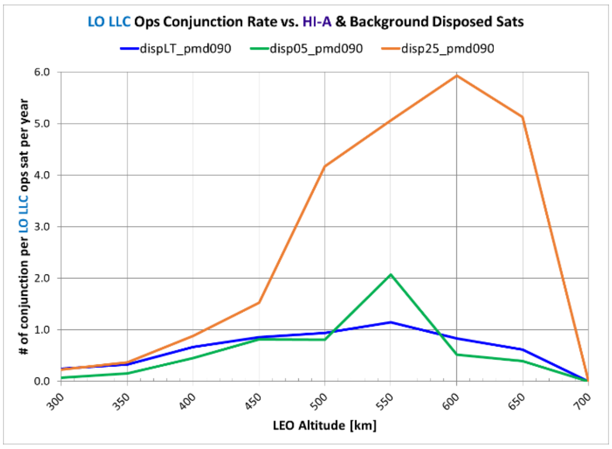

Figure 7. LO LEO (LO A-G) active satellite conjunctions versus HI LEO (HI-A) and background

It is notable that the effect due to the disposal time, 25 versus 5 years, appears to have more effect than the post-mission disposal success rate. This is the opposite of what has been observed for controlling the growth of the debris environment where the post-mission disposal success rate has been observed to have more effect [11][1].

The distribution of average conjunction rates from the low-thrust disposal option is much more evenly distributed which would be expected as the disposing satellites spend similar amounts of time in each altitude range.

The traffic level for the HI LEO was also varied to observe the effects on average number of conjunctions per year. Figure 8 shows three levels of LEO HI traffic, each representing a doubling of the traffic over the next lower scenario. In all these cases there was a 5-year disposal time and a 90% post-mission disposal success rate. The initial step from HI-A to HI-AC does not see a doubling of the average conjunction rate with the doubling in the HI LEO traffic. This is likely due to the inclusion of both background and HI LEO conjunctions with the LO LEO constellation, so the doubling of the HI LEO population is not a doubling of the overall population. As the number of HI LEO satellites increases that constellation becomes a large fraction of the total population transiting the LO LEO altitudes.

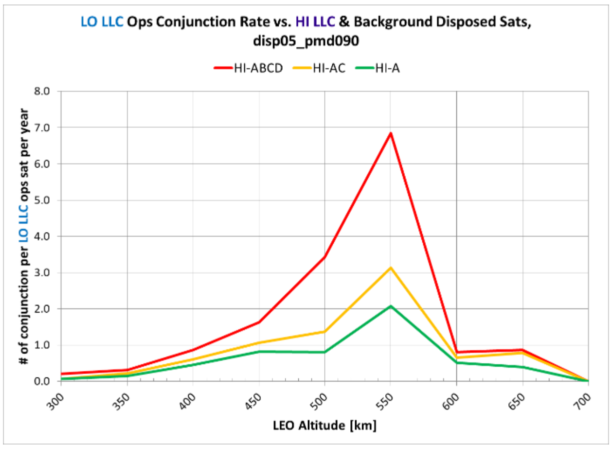

Figure 8. LO LEO (LO A-G) active satellite conjunctions versus HI LEO and background 5-year disposal 90% post-mission disposal

5.3 High LEO disposed satellites

Because the conjunction environment is relative to the satellites of interest this section looks at the average conjunction rates seen by satellites in the HI LEO constellation as they are being disposed and passing through the lower parts of LEO.

Figure 9 shows a plot of average number of conjunctions per year as a function of post-mission disposal success rate. As in the previous section the different success rates have relatively small effects on the overall average conjunction rates. At the disposal altitude the average conjunction rate is directly related to the post-mission disposal success rate. The higher conjunction rates at altitudes above the disposal altitude for the 5-year disposal scenarios are likely due to satellites that failed on their disposals at the intermediate altitudes. Further investigation into these rates and their sources will provide more insight.

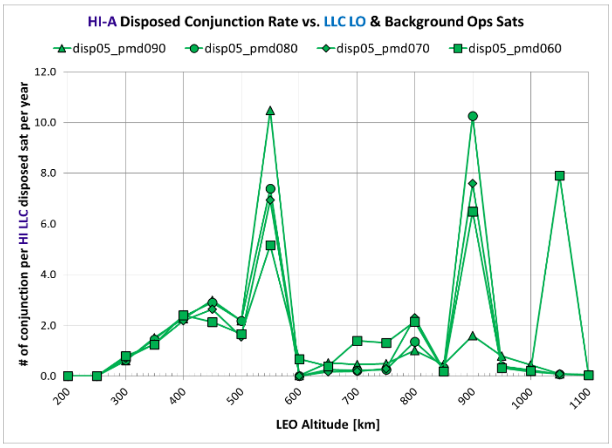

Figure 9. HI LEO (HI-ABCD) conjunctions versus LO LEO and background for 5-year disposal

Figure 10 shows the average number of conjunctions per year by altitude of the disposed satellites from HI-A against the LO LEO and background populations. As with the results from the LO LEO average conjunction rates in Figure 7 there are noticeable peaks in the altitude regions where the HI LEO satellites are initially disposed. Also, the average conjunction rate for the 25-year disposal is significantly higher than for the 5-year disposal as was seen previously. This may be amplified by the interactions between the disposed satellites in this region.

The narrowness of the peaks would support the previous hypothesis that satellites are spending most of their disposal time in the region around where they were initially disposed, the highest part of their disposal.

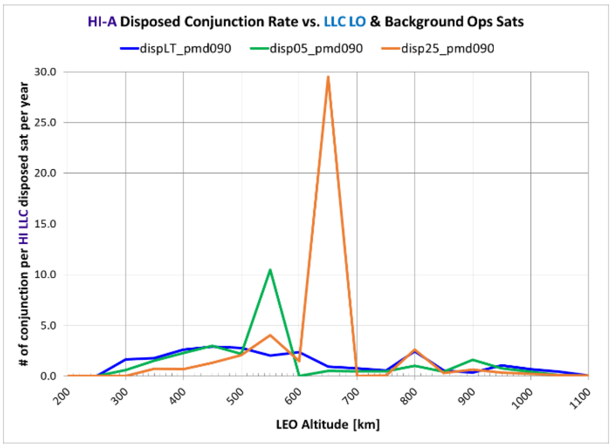

Figure 10. HI LEO disposed conjunctions versus LO LEO ((LO-A-G) and background for 90% post-mission disposal

The low thrust disposal scenario again sees a much more evenly distributed and lower average conjunction rate although comparable to the 25-year and 5-year disposals at low altitudes as the natural decay rate becomes similar to that produced by the low thrust system. Increases in the average number of conjunctions per year can be seen at the altitudes where the LO LEO constellation resides, and the overall population increases.

The average conjunction rates for HI LEO satellites in the 800-850 km region for the 25-year disposal scenario which is above the disposal altitude may be due to failed disposals that left the satellites in these orbits. The higher numbers of HI LEO satellites in the scenarios that show these features and that they are noticeable in the regions where there are the most background objects with which to conjunct are consistent with this supposition. Further examination of results will be conducted to confirm or refute the supposition.

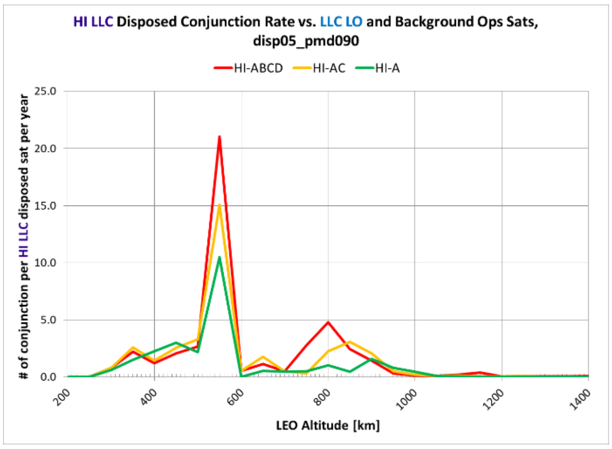

Figure 11. HI LEO disposed satellite conjunctions versus LO LEO (LO-S-G) 5-year disposal, 90% post-mission disposal

Figure 11 shows the distribution of conjunction rates for three different HI LEO traffic levels for the 5-year disposal at 90% success scenario. The systematic increase in conjunctions in the vicinity of the disposal altitude can clearly be seen with the increase in satellite traffic.

5.4 Background objects

A third perspective from which to examine the conjunction environment is from that of the background population. This includes all the operational satellites that are not a part of the HI LEO or LO LEO constellations. These objects have a greater spread in operational orbits and disposal orbits than the much more uniform large constellations.

Figure 12 shows the average conjunction rates for the operational background population over a range of post-mission disposal types and success rates for the full HI LEO constellation (HI-ABCD). The average conjunction rates also include conjunction with the background population including the non-active background objects.

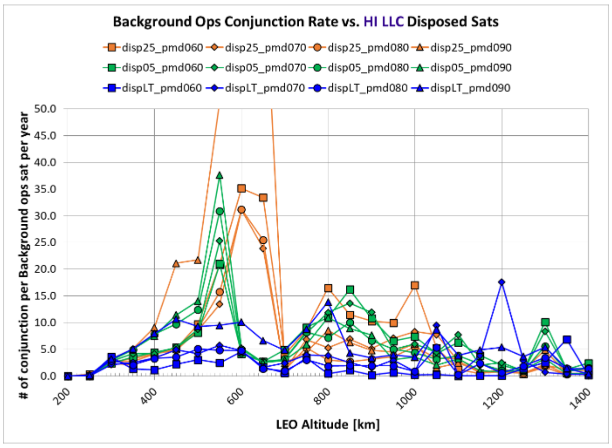

Figure 12. Background operational satellite conjunctions for various HI LEO (HI-ABCD) scenarios

The peaks in average number of conjunctions per year can be seen at the altitudes of the HI LEO 25-year and 5-year disposal orbits for the corresponding scenarios as were observed in previous figures. As in the previous cases the average conjunction rates are significantly higher for the 25-year disposal scenarios than for the 5-year disposal scenarios. The variations in the average conjunction rates for the 25-year and 5-year scenarios at altitudes above the corresponding disposal altitudes may be due to random disposal failures that occurred for the HI LEO satellites as well as the interactions with the HI LEO satellites that failed near their operational altitudes.

The low thrust disposal scenarios show a consistently low and relatively even distribution of average conjunction rate, also consistent with previous perspectives and with the disposing satellites' even distribution in time spend at each altitude. Generally, the higher post-mission disposal success rates for the low thrust disposal scenarios correspond to somewhat higher average number of conjunctions pe year.

6 ENVIRONMENTAL EFFECTS PARAMETERS

In [1] and [10] several parameters were examined for their ability to relate physical and operational characteristics of constellations to their effect on the future debris environment. The undisposed mass per year (UMPY) was noted as one such parameter which correlated with the future debris population.

UMPY is defined in Eq. 1.

$$UMPY = (1 - PMD)\frac{n_{sats} \times mass}{lifetime} \qquad (1)$$

Where:

n_{sats} = number of satellites in the operational constellation

mass = mass of a satellite in kg

PMD = Fractional success rate for post-mission disposal

Lifetime = operational satellite lifetime in year

UMPY captures several parameters that have been found to strongly influence the evolution of the debris environment including the post-mission disposal success rate and the mass of objects left in long-term orbits which can result in future debris.

Although UMPY was designed to represent the effect on the debris environment this study provided an opportunity to see if it also showed some correlation with conjunction environment. Although satellite mass will not play a role in the average conjunction rate, the post-mission disposal rate would reflect the number of satellites left in orbit for longer times, increasing their potential for conjunctions.

Table 4 shows a range of different constellation configurations and their corresponding UMPY values for different operations scenarios. They represent a sample of different constellation scenarios and the associated UMPY values.

Table 4. Undisposed mass per year for constellation configurations

Const	Total Sats	Mass (kg)	Lifetime (years)	PMD Success	UMPY (kg)
HI LEO					
A	5000	147	5	0.9	14,700
B	5000	147	5	0.8	29,400
C	5000	147	5	0.7	44,100
D	5000	147	5	0.6	58,800
LO LEO					
A	5000	268	5	0.95	13,400
B	5000	268	5	0.9	26,800
C	5000	268	5	0.85	40,200
D	5000	268	5	0.9067	25,000
E	5000	268	5	0.75	67,000
F	5000	268	5	0.7	80,400
G	5000	268	5	0.65	93,800
COMBINATIONS					
HI-ABCD	20000	147	5	0.99	5880
LO-BDF	15000	268	5	0.95	40,200
HI-B+ LO-G	10000	147-268	5	0.9	41,500

A number of constellation configuration and operations scenarios UMPY values were plotted in Figure 13 with the corresponding cumulative number of conjunctions for background operational satellites. The plot does show a reasonable correlation between the background operational satellite cumulative conjunction rates and the corresponding value of UMPY. Further examination with a wider variety of cases will better determine the level of robustness of the relationship.

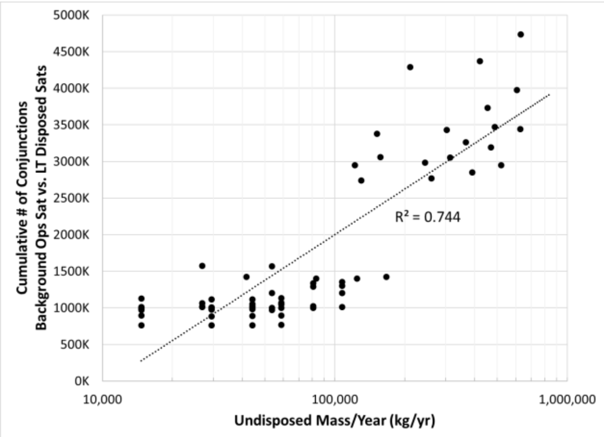

Figure 13. Relationship between undisposed mass per year and cumulative number of conjunctions for background operational satellites

7 CONCLUSIONS

This study examined the conjunction environments produced for different subsets of the future orbital population under different space traffic scenarios that included differing levels of large constellation activity, different post-mission disposal success rates and different methods for post-mission disposal. These variables are similar to those used for analyses performed when examining the possible future evolution of the orbital debris environment.

It was observed that some of the parameters found to be significant for control of the debris environment have differing effects both in relative magnitude and in direction with respect to the conjunction environment. Examples of this are the post-mission disposal success rate and post-mission disposal duration.

For the cases examined the post-mission disposal duration had more of an effect on the conjunction environment in the regions where the disposed satellites resided than did the post-mission disposal success rate. This is the opposite of what has been found for orbital debris mitigation where the post-mission disposal success rate is generally more significant than the disposal duration. The 25-year disposal scenarios generally produced a much higher average conjunction rate environment than the 5-year disposal scenarios.

These results suggest that as Earth orbit becomes more crowded it will be important to consider different aspects of space safety and safety space operations holistically rather than discretely. The actions that improve one aspect of space safety may degrade other aspects. A balance needs to be found in order to plot the best path forward. It will as be important to consider the relative effects of different aspects of space safety when finding that holistic balance. Some issues have greater consequences or are less easy to mitigate than others and considerations for alleviating those should take a higher priority than more easily managed problems.

The scenarios examined in the paper represent only a fraction of those run for the study. Future work will extend the data analysis to a broader range of scenarios as well as include direct comparisons between scenarios and both conjunction and corresponding orbital debris environments.

As the operating environment in space continues to expand and diversify, viewing it as a whole will become increasingly important for ensuring the space environment remains safe for operations.

8 REFERENCES

1. Henning, G.H., M. E. Sorge, G. E. Peterson, A.B. Jenkin, J. P. McVey, D.L. Mains, “Impacts of Large Constellations and Mission Disposal Guidelines on the Future Space Debris Environment,” IAC-19,A6,2,7,x50024, 70th International Astronautical Conference, Washington D.C., USA, 21-25 October 2019

2. Jenkin, A.B., Sorge, M.E., Peterson, G.E., McVey, J.P., Yoo, B.Y., “100-Year Low Earth Orbit Debris Population Model,” Paper No. AAS 11-410, AAS/AIAA Astrodynamics Specialists Conference, Girdwood, AK, July 31- August 4, 2011

3. Jenkin, A.B., Sorge, M.E., McVey, J.P., Peterson, G.E., Yoo, B.Y., “MEO Debris Environment Projection Study,” Proceedings of the Sixth European Conference on Space Debris, Darmstadt, Germany, April 22-25, 2013 (ESA SP-723, August 2013)

4. Jenkin, A. B., M. E. Sorge, G. E. Peterson, J. P. McVey, “Recent Enhancements to ADEPT and Resulting Sample Projections of the Future Debris Environment,” IAC-15,A6,2,2,x28103, 66th International Astronautical Conference, Jerusalem, Israel, October 12-16, 2015

5. McClain, W.D., "A Recursively Formulated First-Order Semianalytic Artificial Satellite Theory Based on the Generalized Method of Averaging," Computer Sciences Corporation, CSC/TR-77/6010, Greenbelt, MD, November 1977.Dennis, N.G., “Probabilistic Theory and Statistical Distribution of Earth Satellites,” Journal of the British Interplanetary Society, Vol. 25, 1972, pp. 333-376

6. Sorge, M.E., "Satellite Fragmentation Modeling with IMPACT," AIAA/AAS Astrodynamics Specialist Conference, Honolulu, HI, August 18-21, 2008

7. Inter-Agency Space Debris Coordination Committee (IADC) Debris Mitigation Guidelines, https://www.iadc-home.org/documents_public/view/id/82#u

8. U.S. Government Orbital Debris Mitigation Standard Practices (ODMSP), https://orbitaldebris.jsc.nasa.gov/library/usg_orbital_debris_mitigation_standard_practices_november_2019.pdf

9. Peterson, G.E., Sorge, M.E., McVey J.P., Gegenheimer, S., Henning G.A., "Tracking Requirements in LEO for Space Traffic Management in the Presence of Proposed Small Satellite Constellations," IAC-18,A6,7,6,x43991, 69th International Astronautical Conference, Bremen, Germany, 21-25 October 2018

10. Henning, G.A., Sorge, M.E., Peterson, G.E., Jenkin, A.B., Mains, D.L., McVey J.P., "Parametrization Large Constellation Post-Mission Disposal Success to Predict the Impact to Future Space Environment." Journal of Space Safety Engineering, August, 2020

11. Bastida Virgili, B., Dolado, J.C., Lewis, H.G., Radtke, J., Krag, H., Revelin, B., Cazaux, C., Colombo, C., Crowther, R., Metz, M., "Risk to space sustainability from large constellations of satellites," Acta Astronautica 126 (2016) 154-162