Effects of CubeSat Deployments in Low-Earth Orbit

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ABSTRACT

Long-term models, such as NASA's LEGEND (LEO-to-GEO Environment Debris) model, are used to make predictions about how space activities will affect the manner in which the debris environment evolves over time. Part of this process predicts how spacecraft and rocket bodies will be launched and remain in the future environment. This has usually been accomplished by repeating past launch history to simulate future launches.

The NASA Orbital Debris Program Office (ODPO) has conducted a series of LEGEND computations to investigate the long-term effects of adding CubeSats to the environment. These results are compared to a baseline "business-as-usual" scenario where launches are assumed to continue as in the past without major CubeSat deployments. Using these results, we make observations about the continued use of the 25-year rule and the importance of the universal application of post-mission disposal.

1 INTRODUCTION

Recent studies on the evolution of the orbital debris environment in Low-Earth Orbit (LEO) [1,2] have suggested that the current environment is unstable and population growth is inevitable, even if future space launches were to cease, due to the production of small debris from increased on-orbit collisions. The actual growth of satellites in LEO may turn out to be higher than predicted by such studies because of unanticipated increases in launch frequency and quantities of objects launched.

For example, due to the likelihood of deployments of large numbers of small satellites and the recent proposal of mega-constellations, small satellites present several new and unique challenges to the space environment and to other operational spacecraft. The increased collision risks to other operational spacecraft are inevitable if the small satellites cannot be tracked and do not have collision avoidance maneuver capability. Adding hundreds of small satellites to the environment on a regular basis will increase collision probabilities in the future environment. Placing hundreds or thousands of small satellites on similar 25-year decay orbits could create unprecedented collision-avoidance problems for the International Space Station (ISS) and other human activities in LEO. In addition, these small satellites typically do not include control systems capable of deorbiting the satellite after its mission lifetime, thus post-mission disposal (PMD) is not always possible in order to move such a spacecraft into a lower orbit that would naturally decay within 25 years, as is currently the standard for other payloads. Though PMD technologies such as deployable deorbit sails and tethers are currently under development for these small satellites, a universal application has not yet been adopted.

Most of the current national and international orbital debris mitigation guidelines are based on studies where the future environment is predicated on past launch activity, and does not contain such large deployments of hundreds or thousands of small satellites. Consequently, questions have arisen whether the currently accepted standards (e.g., the 25-year rule) are adequate to meet the expected proliferation of small satellites.

This paper presents an analysis of how the future LEO environment is affected by different small satellite launch scenarios, where the small satellites are exclusively comprised of all CubeSats. Each future scenario is compared with a baseline population that represents the continuation of historic launch activity without large CubeSat deployments. The results of this study indicate that the universal application of the 25-year rule to CubeSats and other spacecraft is critical to avoid the deterioration of the orbital environment at mid-LEO altitudes of approximately 600 – 1000 km.

The outline of this paper is as follows. Section 2 discusses the implementation of the future projection simulations, with details for the baseline population given in section 2.2 and the CubeSat scenarios given in section 2.3. Section 3 shows results of the simulations in terms of effective number of objects (section 3.1) and catastrophic collisions (section 3.2). Finally, the paper concludes in section 4 with recommendations.

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2 IMPLEMENTATION

2.1 Background

All simulations presented here were performed using LEGEND, a LEO-to-GEO Environment Debris model, which is the tool used by ODPO for long-term debris environment studies [3,4]. A key component in LEGEND is a three-dimensional collision probability evaluation module. This module is designed to accurately model the three-dimensional distribution of collisions expected around the Earth based on the orbits of the colliding bodies. Collision probabilities are calculated for future projection only. For the purposes of this study, only objects with a characteristic length of 10 cm and larger are included in collision consideration. The NASA Standard Breakup Model [5] is applied to the outcome of a collision, generating fragments based on distributions of breakup fragment size, area-to-mass ratio, and delta-velocity.

Critical metrics for comparison across scenarios include the effective number of LEO-crossing objects and the cumulative number of catastrophic collisions that occur in the future projection. The effective number of LEO-crossing objects is defined as the effective number of 10 cm or larger objects crossing the LEO region multiplied by the fraction of the time each object resides between 200 – 2000 km altitude. A catastrophic collision is characterized by an impactor kinetic energy-to-target mass-ratio of 40 J/g or higher. The more massive object involved in a collision is defined as the target while the less massive object is defined as the projectile. In a catastrophic collision, both the target and the projectile are completely fragmented whereas in a non-catastrophic collision, only a small fraction of the target is chipped away. In general, catastrophic collisions produce many more fragments than non-catastrophic collisions [4].

2.2 Baseline

The baseline population in this study depicts a future environment without the introduction of cluster deployments of CubeSats. Actual historical launches and evolution from 1957 through 2014 are simulated as the initial condition for future traffic projection, which runs for 200 years starting in 2015. Future launches repeat the historical launch cycle from 2007 to 2014 launch traffic cycle. The rate of future explosions is set to zero, assuming 100% passivation in the future projection, and the mission lifetime for payloads is set at 8 years. A specified percentage of spacecrafts and rocket bodies are repositioned in decay orbits following PMD maneuvers, where they will re-enter the atmosphere within 25 years. The baseline population is projected using two PMD success rates of 60% and 90%, respectively. These are used for comparisons with the future scenarios in section 3. Each simulation includes 100 Monte Carlo runs to ensure a thorough statistical sampling of the future environment. Results shown are averages over all Monte Carlo runs.

Objects are categorized as either a regular intact (I) or a regular fragment (F). Regular intacts represent rocket bodies, payloads, and spacecraft of historical and future launches. Regular fragments include historical fragments (generated prior to 1 January 2015) and fragments from three types of collisions in future projection – regular intact-intact (I-I), intact-fragment (I-F), or fragment-fragment (F-F).

Fig. 1 shows a comparison of the average total effective number of objects (regular intacts plus regular fragments) for the PMD 60% and PMD 90% cases over the 200-year future projection simulation. The rate of population growth is approximately the same between the two PMD success cases for the first quarter of the future projection period. After this point, the growth rate in the PMD 60% case increases, while that of the PMD 90% case remains relatively constant due to the large number of objects removed the environment through PMD. After 200 years, the population in the PMD 60% case more than doubles the initial population. Clearly, the 90% PMD success rate mitigates the overall growth of the population, resulting in an approximately 23% lower effective number of objects at the end of the 200 year projection as compared to the 60% PMD case.

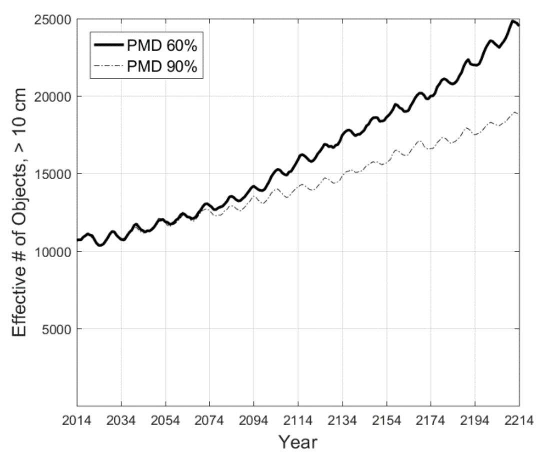

Figure 1. Effective number of objects in LEO, ≥ 10 cm, in baseline population over 200-year projection with a PMD success rate of 60% (solid line) and 90% (dash-dotted line)

Fig. 2 shows the average number of cumulative catastrophic collisions of LEO-crossing objects for the PMD 60% and PMD 90% cases. The PMD 90% case shows relatively constant growth of cumulative catastrophic collisions, while in the PMD 60% case the rate begins to increase after approximately 80 years. At the end of the 200 year projection, the PMD 90% case results in approximately 24% fewer catastrophic collisions than the PMD 60% case.

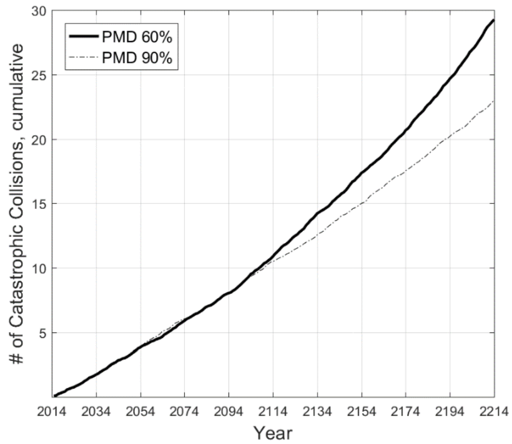

Figure 2. Cumulative number of catastrophic collisions in LEO region, baseline population, over 200-year projection with a PMD success rate of 60% (solid line) and 90% (dash-dotted line)

2.3 CubeSat Scenarios

The CubeSat traffic scenarios use the same initial conditions and launch traffic cycle for regular intacts as the baseline scenario, and additionally deploy various sizes of CubeSats from a small satellite deployment system in the LEO region. The mission lifetime of each CubeSat deployed in LEO is assumed to be two years for all future scenarios, during which time each CubeSat will apply its own set of collision avoidance maneuvers. After its mission lifetime, the CubeSat is placed in a post-mission disposal orbit where it will decay within 25 years with a 0%, 60%, or 90% probability of success.

The standard [6] defines a 1-unit (1U) CubeSat as having a cubical dimension of 10 cm on each side and a mass of approximately 1 kg. Here, CubeSat traffic scenarios include 1U, 3U, and 6U CubeSats in the future projection. A standard ODPO software tool was used to estimate the empirical area-to-mass ratios (A/m) of actual CubeSats from observed orbital decay of historical small satellite launch [7]. The 1U and 3U CubeSats launched in future scenarios have an A/m selected from these historical launches. However, due to limited historical data for 6U CubeSats, a Gaussian distribution was created based on the average A/m of each 6U CubeSat with a 25% standard deviation.

This study makes the following assumptions: 1) there are no launch failures or explosions of any CubeSats in the future environment, 2) the deployment system can support the launch of hundreds of CubeSats at a given time, and 3) each CubeSat does not perform any collision avoidance once in a PMD orbit.

Three CubeSat traffic scenarios are considered in this study, termed J1, J2, and J3. In scenario J1, CubeSats are deployed from the 600 – 1000 km altitude range and have PMD success rates of 60% and 90%, the same PMD rate of regular intacts. Scenario J2 follows the same scheme as scenario J1, except the deployed CubeSats do not follow any post-mission disposal compliance (0% PMD success rate for CubeSats). In scenario J3, the PMD compliance rates are the same as in J1 (60% and 90%), but this time the lower bound of the CubeSat deployment altitude range is set to 650 km, which is just beyond a naturally decaying orbit of 25 years. This parameter change will highlight how a small change in deployment orbits can alter the future environment at altitudes greater than 600 km. Tab. 1 details the CubeSat deployment conditions for scenarios J1 through J3.

Table 1. Deployment altitude ranges and PMD compliance rate for regular objects (i.e., spacecraft, rocket bodies, operational debris, and fragments) and CubeSats, scenarios J1 – J3

Scenario	PMD % (regular objs.)	PMD % (CubeSats)	Deployment Altitude Range
J1	60%	60%	600 km – 1000 km
	90%	90%	
J2	60%	0%	
	90%	0%	
J3	60%	60%	650 km – 1000 km
	90%	90%	

Tab. 2 shows the number of CubeSats deployed in scenarios J1 through J3, broken down by 1U, 3U, and 6U types. CubeSats deposited in the LEO environment during future propagation and each deployment is independent of the 8-year traffic cycle. Based on historical CubeSat launch behavior, the CubeSats are deployed in a sun-synchronous orbit and share the same orbital elements as their parent deployment system, which will also have PMD capability.

Table 2. Number of CubeSats added to the environment via large-scale deployments over 200 years

CubeSat – U type	J1 and J2	J3
1U CubeSat	29418	29460
3U CubeSat	12816	13044
6U CubeSat	8588	8467
Total # of CubeSats	50822	50971

For each scenario, the same traffic cycle of CubeSat deployments is used for each Monte Carlo run and each PMD success rate. Starting in 2016, there are two massive deployments per year at day 60 and day 240, where all CubeSat payloads are launched from a deployment system. Each massive deployment consists of a total volume of 300U CubeSats, comprised of a random combination of 1U, 3U, and 6U CubeSats. The deployment system moves to a decay orbit after each massive deployment while the parent rocket body is immediately deorbited after use.

Each of the LEO objects of at least 10 cm are individually assigned one of six different object types. The first two object types are regular intacts and regular fragments as defined in the baseline scenario. The third object type is CubeSat intacts that represent the 1U, 3U, or 6U CubeSats launched in the future environment. The fourth object type is a CubeSat fragment, created by a breakup event of a parent CubeSat intact. Operational debris is the fifth object type that represents the CubeSat deployment system. Finally, the final object type depicts the additional regular fragments in the environment that are generated from a regular intact or regular fragment colliding with a CubeSat object (e.g., CubeSat intact, CubeSat fragment, or CubeSat operational debris). These objects do not appear in the baseline datasets and are identified as "delta" fragments in this study.

2.4 Orbital Lifetimes

Tab. 3 shows the natural orbital lifetime of all deployed CubeSats at the time of deployment, which marks the beginning of mission (BOM) before any collision-avoidance or PMD maneuvers are applied. This gives an indication of how many CubeSats would naturally decay within 25 years without the application of any PMD maneuvers. Only 9% of deployed CubeSats in scenarios J1 and J2 reside in a naturally decaying orbit of less than or equal to 25 years, compared to only 2.2% in scenario J3. Thus, even a small increase in deployment altitude can lead to an increase in the number of CubeSats in orbit, especially if these small satellites fail to deploy properly or do not follow PMD guidelines.

Table 3. Percentage of CubeSat population with given range of natural decay lifetime at BOM

Orbital Lifetime	J1 & J2	J3
1 – 5 years	0.1%	0.0%
6 – 10 years	0.8%	< 0.01%
11 – 25 years	8.1%	2.2%
≥ 25 years	91.1%	97.8%

3 RESULTS

3.1 Effective Number of objects (≥ 10cm, LEO)

Fig. 3 and Fig. 4 show the growth of the effective number of objects over the 200-year projection for baseline (thick black line) and scenarios J1 through J3 with PMD compliance rates of 60% and 90%, respectively. Comparing curves for scenarios J1 (red dash-dot line) and J2 (green dash line) in Fig. 3 illustrates how setting the PMD rate to 0% substantially increases the total number of objects in the future environment. All three scenarios exhibit the same sharp rate of growth until 2043, the year when CubeSats launched in 2016 begin to be removed from the environment after their 25-year PMD decay orbit expires. After this point, the rate of object growth slows for scenarios J1 and J3 (thin blue line) to approximately match that of the baseline population. However, scenario J2 exhibits a steady rise in the effective number of objects over the full 200 years due to the lack of PMD for CubeSat intacts. Increasing the deployment altitude of CubeSats (as in scenario J3) also causes a slight increase in the effective number of objects after 200 years since more of the CubeSats lie outside of a natural decay lifetime of 25 years.

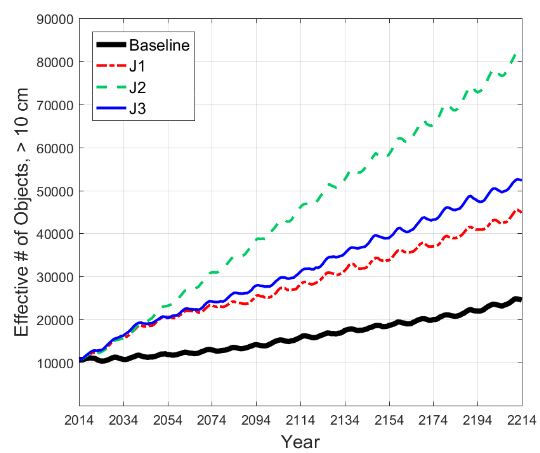

Figure 3. Effective number of objects in LEO, ≥10 cm, over 200-year projection with a PMD success rate of 60%, baseline and scenarios J1 – J3. Note the steeper growth for scenario J2, where only non-CubeSats observe PMD.

Fig. 4 illustrates the effectiveness of increasing the PMD compliance rate to 90% for CubeSats as well as other spacecraft. The effective number of objects at the end of the 200-year projection is reduced by approximately 35% in scenario J1 and almost 40% in scenario J3. Scenario J2 sees a reduction in the number of regular intacts and regular fragments under a 90% (background) PMD success rate, but since CubeSats do not undergo any PMD in this scenario, the total effective number of objects at the end of the 200-year projection is not significantly reduced. The unlimited growth of CubeSats in this case swamps the beneficial effects of other satellites observing the 25-year rule.

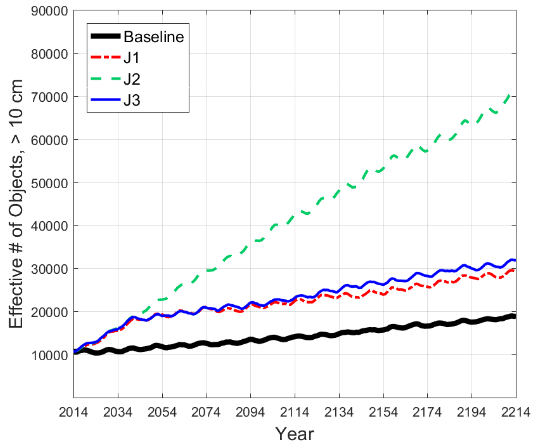

Figure 4. Effective number of objects in LEO, ≥10 cm, over 200-year projection with a PMD success rate of 90%, baseline and scenarios J1 – J3. Note the steeper growth for scenario J2, where only non-CubeSats observe PMD.

Tab. 4 shows the effective number of ≥10 cm objects in LEO after 200 years, broken down by object type and compared to the baseline population for a PMD compliance rate of 60%. The total effective number of objects for all scenarios increases significantly from the baseline case, largely due to the number of CubeSat intacts and "delta" fragments. Note that even though scenario J1 and J2 have the same inputs (CubeSat traffic cycle and deployment altitudes), the PMD compliance rate of small satellites is set to zero for scenario J2, so the overall increase in effective number of objects for scenario J2 is quite drastic – over 200%. Between scenarios J1 and J3, there is also a clear increase in the number of CubeSat intacts, CubeSat fragments, and "delta" fragments due to longer orbital lifetimes for the CubeSats that fail PMD in scenario J3.

Table 4. Comparison of effective number of objects in LEO, ≥10 cm over 200-year projection with a PMD success rate of 60%, baseline and scenarios J1 – J3

PMD 60%				
Object Type	Baseline	J1	J2	J3
CubeSat, op. debris	0.0	48.9	48.9	48.0
CubeSat, fragment	0.0	31.2	147.5	46.5
CubeSat, intact	0.0	11284.1	28602.9	13825.5
Regular Fragments (I-I, I-F, F-F, hist.)	19769.6	20111.6	19398.8	20291.6
"delta" Fragments	0.0	8617.4	27878.4	13449.1
Regular Intacts	4741.5	4721.7	4668.7	4699.9
Total	24511.1	44815.0	80745.3	52360.5
% increase	-	82.8%	229.4%	113.6%

Tab. 5 shows the effective number of ≥10 cm objects in LEO after 200 years, broken down by object type, with a PMD compliance rate of 90%. The number of Cubesat intacts in orbit after 200 years remains constant for scenario J2 between background PMD 60% and background PMD 90%, which is expected due to the PMD compliance rate of Cubesats set to zero. For scenarios J1 and J3, the number of "delta" fragments drop significantly, compared to the modest decrease in "delta" fragments between J2 with background PMD 60% and J2 with background PMD 90%.

Table 5. Comparison of effective number of objects in LEO, ≥10 cm over 200-year projection with a PMD success rate of 90%, baseline and scenarios J1 – J3

PMD 90%				
Object Type	Baseline	J1	J2	J3
CubeSat, op. debris	0.0	49.0	49.0	48.0
CubeSat, fragment	0.0	9.2	129.1	15.4
CubeSat, intact	0.0	7494.1	28610.4	8702.4
Regular Fragments (I-I, I-F, F-F, hist.)	14975.2	14834.1	13191.4	14359.7
"delta" Fragments	0.0	2875.3	23817.6	4851.0
Regular Intacts	3865.8	3860.3	3809.7	3855.0
Total	18841.0	29121.9	69607.1	31831.5
% increase	-	54.6%	269.4%	68.9%

Fig. 5 – 10 show the difference in effective number of objects between the baseline population and scenarios J1-J3, respectively, at different altitudes in LEO at the end of the 200-year projection for PMD 60% and PMD 90% cases. The increase in effective number of objects seen in the CubeSat scenarios is distributed throughout the deployment altitudes (600 – 1000 km for scenarios J1 and J2, 650 – 1000 km for scenario J3). Increases that are similar across all scenarios are noticeable at lower altitudes due to natural decay of the CubeSats at lower altitudes and PMD maneuvers of CubeSats in scenarios J1 and J3. The higher deployment altitudes in scenario J3 (Fig. 9) yield slightly elevated populations at altitudes of 700 – 1000 km as compared to scenario J1 (Fig. 5). In Fig. 7, however, with a PMD success rate of 0% for CubeSats, scenario J2 shows a dramatic increase in the population at altitudes of approximately 550 – 1000 km. In the 700 – 800 km range, the effective number of objects is more than six times what was reported in the baseline case, with up to 85% of the population being comprised of CubeSat-related objects (i.e. CubeSat intacts, CubeSat fragments, CubeSat operational debris, and "delta" fragments). This is clearly an effect of not applying PMD to CubeSat objects after their mission lifetimes. Since 91% of the CubeSats deployed in scenario J2 have a natural decay lifetime of greater than 25 years (see Tab. 3), these objects remain in the environment longer, regardless of the PMD compliance rate of the other satellites in the environment. Similar behavior is illustrated in the case of a 90% PMD success rate for CubeSats and regular intacts (Fig. 6, 8, 10).

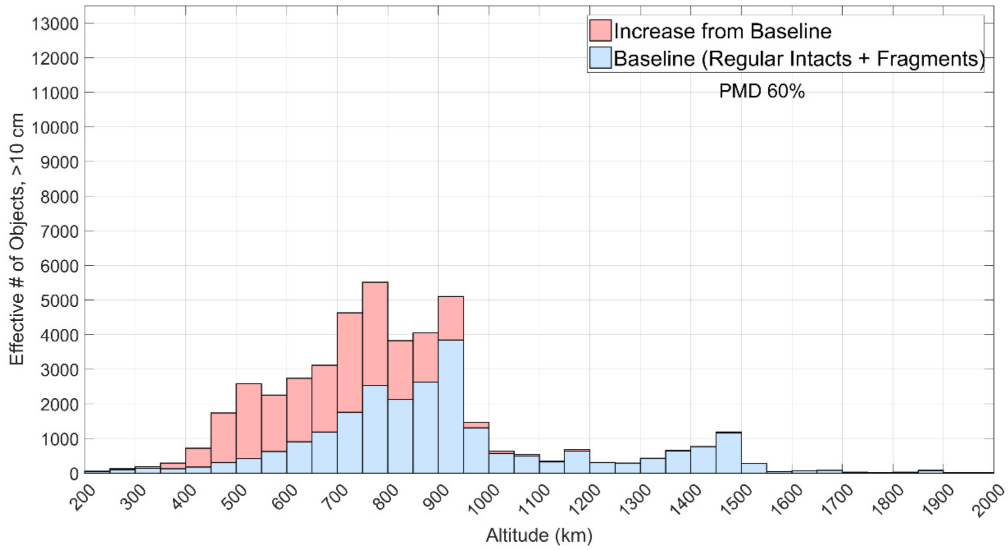

Figure 5. Scenario J1, increase in effective number of objects, ≥10 cm, from baseline population, by altitude (200 – 2000 km, 50 km bins) at the end of 200-year projection for a PMD success rate of 60%

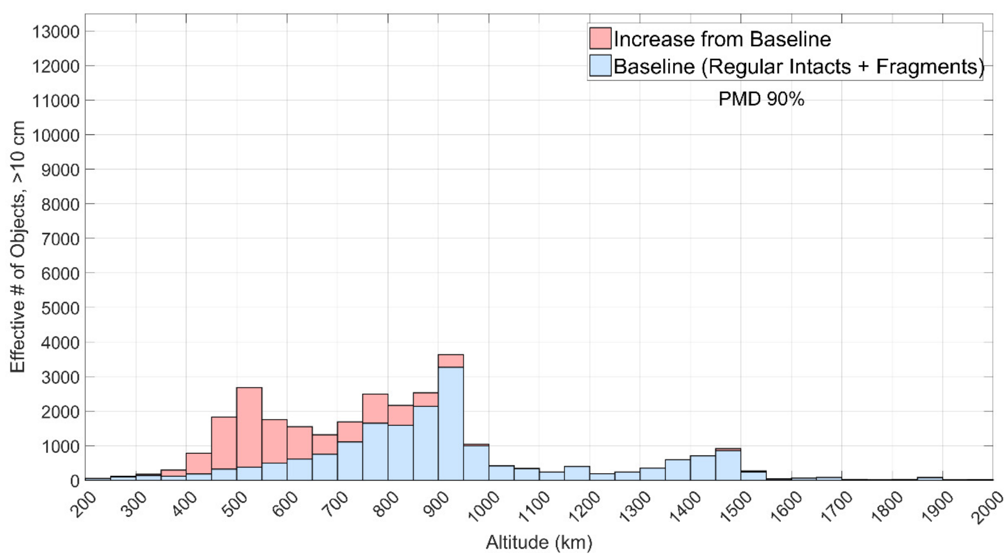

Figure 6. Scenario J1, increase in effective number of objects, ≥10 cm, from baseline population, by altitude (200 – 2000 km, 50 km bins) at the end of 200-year projection for a PMD success rate of 90%

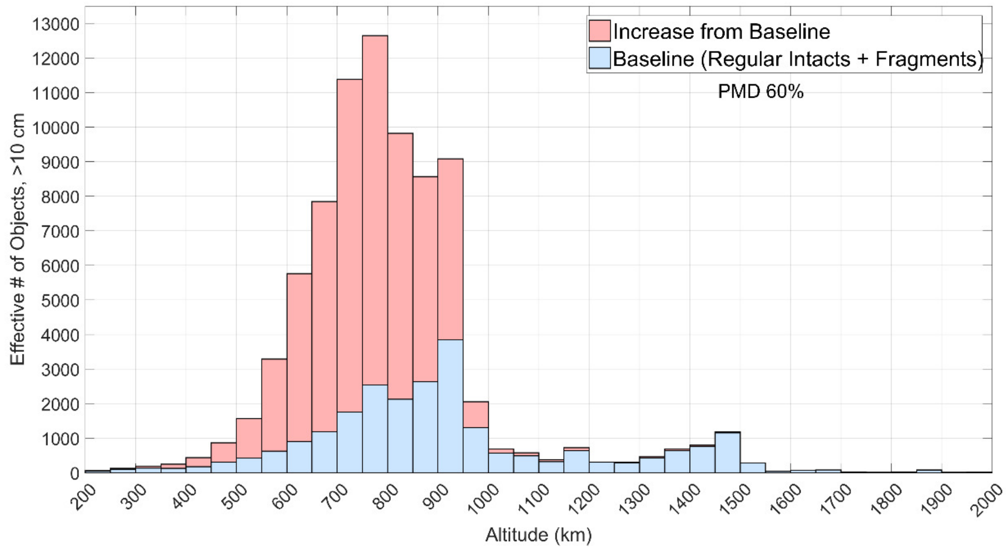

Figure 7. Scenario J2, increase in effective number of objects, ≥10 cm, from baseline population, by altitude (200 – 2000 km, 50 km bins) at the end of 200-year projection for a PMD success rate of 60% (0% PMD for CubeSats)

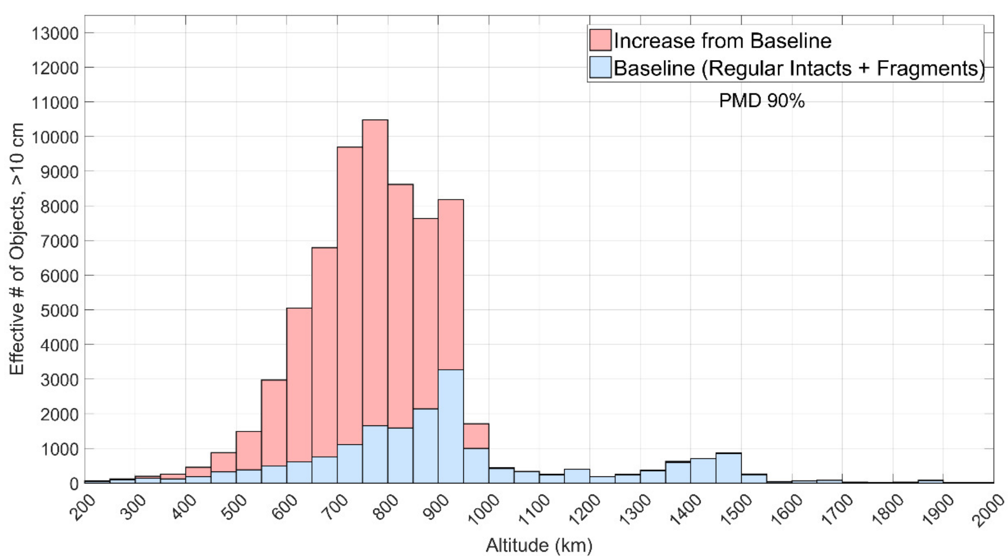

Figure 8. Scenario J2, increase in effective number of objects, ≥10 cm, from baseline population, by altitude (200 – 2000 km, 50 km bins) at the end of 200-year projection for a PMD success rate of 90% (0% PMD for CubeSats)

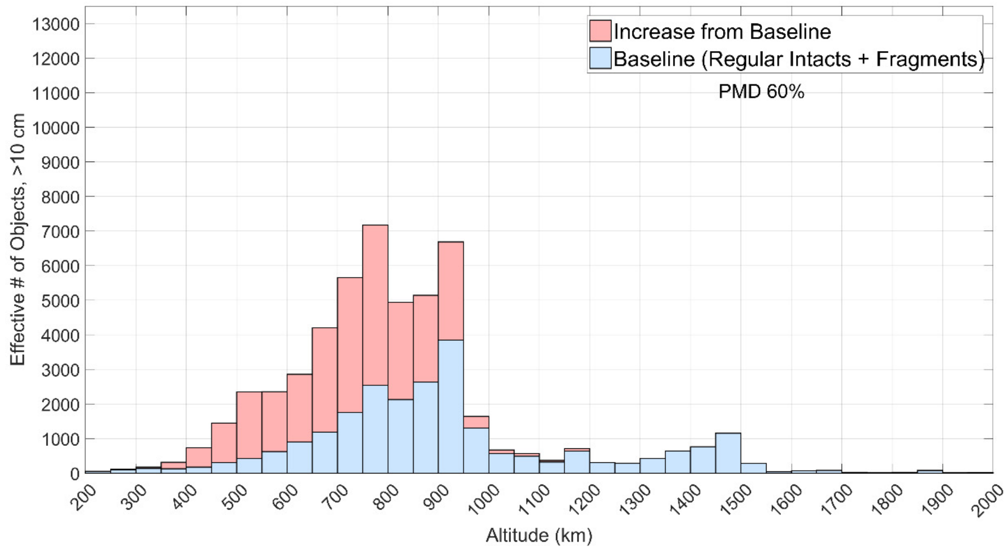

Figure 9. Scenario J3, increase in effective number of objects, ≥10 cm, from baseline population, by altitude (200 – 2000 km, 50 km bins) at the end of 200-year projection for a PMD success rate of 60%

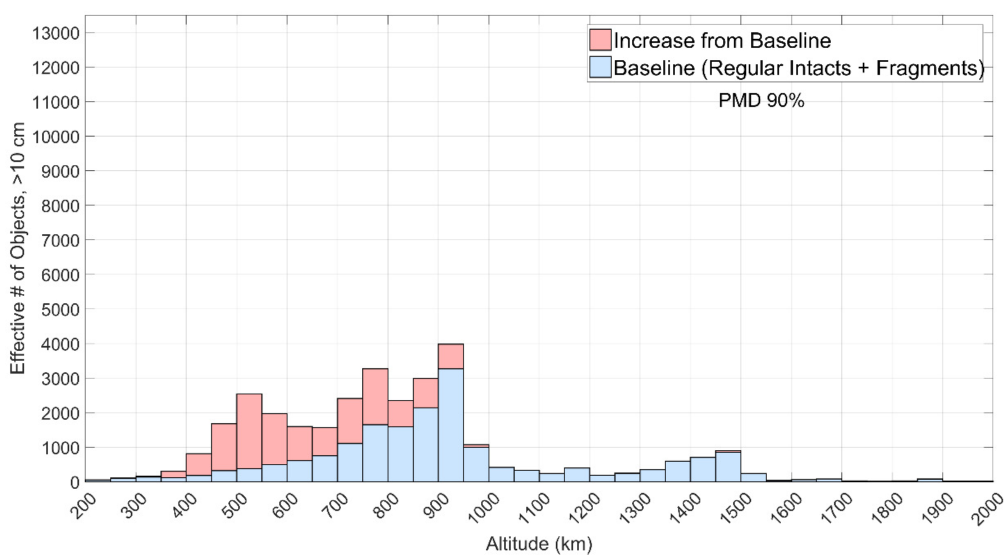

Figure 10. Scenario J3, increase in effective number of objects, ≥10 cm, from baseline population, by altitude (200 – 2000 km, 50 km bins) at the end of 200-year projection for a PMD success rate of 90%

3.2 Catastrophic Collisions

The cumulative number of catastrophic collisions in scenarios J1 through J3 over the 200-year projection with a PMD compliance rate of 60% is shown in Fig. 11, while Fig. 12 illustrates the PMD 90% case. As stated previously, only objects ≥10 cm are considered for collision assessment in this study.

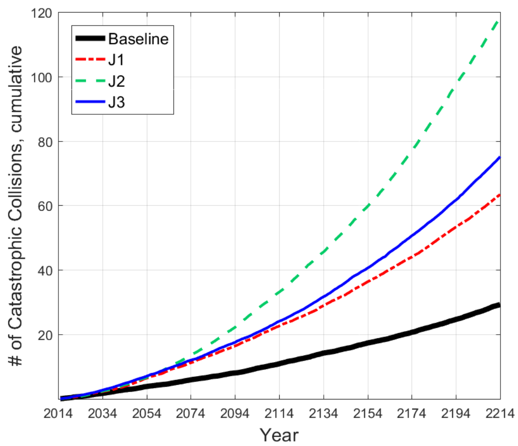

Figure 11. Cumulative number of catastrophic collisions in LEO over 200-year projection with a PMD success rate of 60%, baseline and scenarios J1 – J3

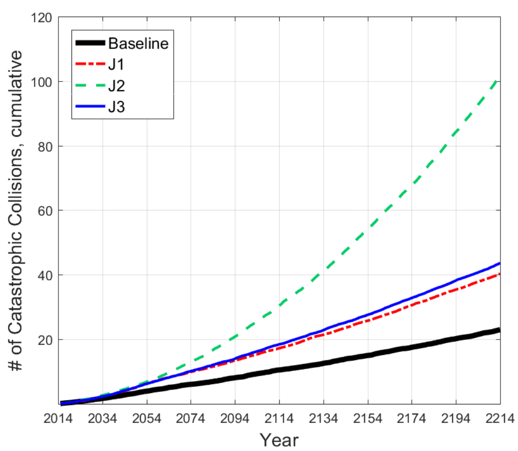

Figure 12. Cumulative number of catastrophic collisions in LEO over 200-year projection with a PMD success rate of 90%, baseline and scenarios J1 – J3

As realized with the effective number of objects, increasing the PMD compliance rate from 60% to 90% for spacecrafts and rocket bodies, while still setting PMD rate for CubeSats to zero as in scenario J2, yields a negligible decrease in the overall collision rate over the 200-year projection.

The cumulative number of catastrophic collisions broken down by collision type (regular F-F, regular I-F, regular I-I, and CubeSat-related) are shown in Tab. 6 for the PMD 60% case and Tab. 7 for the PMD 90% case. CubeSat-related collisions are defined as a collision involving a CubeSat object, whether it collides with another CubeSat object or a regular object.

Table 6. Comparison of cumulative number of catastrophic collisions in LEO over 200-year projection with a PMD success rate of 60%, baseline and scenarios J1 through J3

PMD 60%				
Collision Type	Baseline	J1	J2	J3
CubeSat-related collisions	0.0	33.4	89.5	44.4
Regular F-F	2.3	2.3	2.3	2.4
Regular I-F	12.5	12.4	12.2	13.2
Regular I-I	14.5	15.3	14.6	15.1
Total	29.3	63.4	118.5	75.2
% increase	-	116.5%	305.0%	156.9%

As expected, regular F-F, regular I-F, and regular I-I collisions remain steady over future projection period for both PMD cases. However, the CubeSat-related collisions comprise the majority of the number of catastrophic collisions across all scenarios as seen in Tab. 6 and Tab. 7. It is once again clear that scenario J2, with no PMD applied to CubeSats, produces the worst outcome – an increase in the cumulative number of catastrophic collisions by more than 300% over the baseline population.

Table 7. Comparison of cumulative number of catastrophic collisions in LEO over 200-year projection with a PMD success rate of 90%, baseline and scenarios J1 through J3

PMD 90%				
Collision Type	Baseline	J1	J2	J3
CubeSat-related collisions	0.0	17.9	81.0	22.8
Regular F-F	1.7	1.6	1.7	1.5
Regular I-F	9.7	8.8	8.1	8.4
Regular I-I	11.6	12.1	10.9	11.0
Total	23.0	40.3	101.7	43.7
% increase	-	75.3%	342.2%	89.8%

4 DISCUSSION and RECOMMENDATIONS

This study identifies potential negative effects on the future LEO environment from CubeSat deployments. Adding CubeSats into the environment via a large-scale deployment system yields an increase in both effective number of objects and catastrophic collisions when compared to a “business-as-usual” population. CubeSats accumulate across all of their deployment altitudes, yielding an increase in the number of catastrophic collisions at these altitude regions of high spatial density. However, this population increase can be limited by requiring future CubeSats perform additional collision avoidance from end of mission until reentry, as well as by enforcing PMD compliance for CubeSats since the majority of CubeSats deployed above 600 km will not naturally decay within 25 years.

The effectiveness of PMD applied to CubeSats in addition to other payloads is evidenced by the significant difference in effective number of objects and cumulative catastrophic collisions seen between scenarios J1 (CubeSat PMD success rates of 60% and 90%) and J2 (0% PMD for CubeSats). Therefore, it is recommended that CubeSats follow the same 25-year rule as other payloads in order to avoid deterioration of mid-LEO altitudes (approximately 600-1000 km). It is also not recommended at this time that CubeSats be required to observe a different PMD standard than that applied to their larger cousins; specifically the 25-year rule.

While PMD capabilities for small satellites are still under development, the outcomes of this study indicate that such technology is critical for successful long-term use of satellites in near-Earth space.

5 REFERENCES

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