Intact Derelict Deposition Study

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ABSTRACT

The examination of clusters of derelict objects (abandoned rocket bodies [RB] and non-operational payloads [PL]) in low Earth orbit (LEO) largely has highlighted their unique debris-generating risk. The "pure" clusters are four Russian-created concentrations of "paired" massive objects (i.e., one PL and the RB that deployed it, both in very similar orbits) centered at 775 km, 850 km, 975 km, and 1,500 km. The debris-generating risk from these are significant as both the consequences and probability are larger than a "typical" collision event. The purpose of this study is to examine the context of these clusters relative to all RBs and non-operational PLs (i.e., massive derelicts) that have been deposited over the Space Age. It is observed that 36% of all RBs ever used are still in Earth orbit; it is not getting better as 57% of the RBs deposited over the last 10 years are also still in orbit.

For three key circular orbit regions, the Russians are the overwhelming contributors: In LEO HIGH (650-2,000 km), they are responsible for 69% of the objects (~480 out of ~700); in semi-synchronous orbit (SEMI, 21k ± 3k km) their hardware comprises 70% of the intact derelict population (~63 out of ~90); and in geosynchronous orbit (GEO, 35,786 ± 200 km) 83% (~100 out of ~120) of intact derelict objects are of Russian origin. However, China has "contributed" 41% of total RBs over the last five years in these three vital orbits. China left eight RBs in SEMI in 2018 alone, amounting to 9% of the total abandoned RBs in this region over the Space Age. The observations associated with non-operational PLs are different than for RBs: there is growing use of (1) very low LEO orbits (below 650 km) for smallsats; (2) SEMI for several national positioning, navigation, & timing (PNT) constellations; and (3) GEO by a diverse, global community with large spacecraft. The ambiguity of whether a PL is operational or not, complicates the analysis further.

In summary, this analysis tests the hypothesis that, despite the large number of massive objects deposited in a wide variety of orbits, the clustering of largely paired (i.e., both PLs and associated RBs) in long-lived LEO pose the greatest risk for large debris-generating collisions over the next decade. This study modifies this assertion slightly and suggests the need for a new bi-modal cluster, with peaks around 525 and 625 km, which poses a growing risk for significant debris-generating events.

1 Big Picture Growth

The growth of the orbital debris collision hazard has been largely spawned by hundreds of explosions and collisions that have occurred in Earth orbit over the ~60 years of the Space Age. These events have generated nearly 30,000 debris fragments that have been cataloged by the US Air Force Combined Space Operations Center (CSpOC) of which over 12,000 remain in orbit. [www.Space-track.org] These trackable debris fragments are likely joined by 500,000-900,000 debris fragments that are too small to be tracked yet still sufficiently lethal upon collision to disrupt or terminate operations of a payload. These objects are collectively called lethal nontrackable (LNT) debris. The current debris collision risk is largely from these LNT; future debris collision risk will likely be driven by the massive intact derelict objects that could explode or collide with each other to create more LNT. For this reason, the authors have undertaken a study to examine the growth of the accumulation of intact massive derelict space hardware in Earth orbit.

Figure 1 shows the accumulation of mass in Earth orbit by number (left panel) and mass in metric tons (right panel). There are currently over 3,000 non-operational PLs and nearly 2,200 RBs in Earth orbit comprising ~6 million kg of derelict mass. 36% of all RBs ever used are still in orbit today (i.e., ~2,200 out ~6,000). Coincidentally, 36% of all PLs ever deployed remain in orbit as non-operational PLs (i.e., ~3,000 out of ~8,400) with ~2,000 on-orbit still operational and ~3,400 having already re-entered. In addition to total mass on-orbit, it is critical to examine how these massive intact derelict objects are distributed by altitude, country of origin, and date deposited to get a better understanding of the potential future sources of LNT debris generation from collisions between massive intact derelicts.

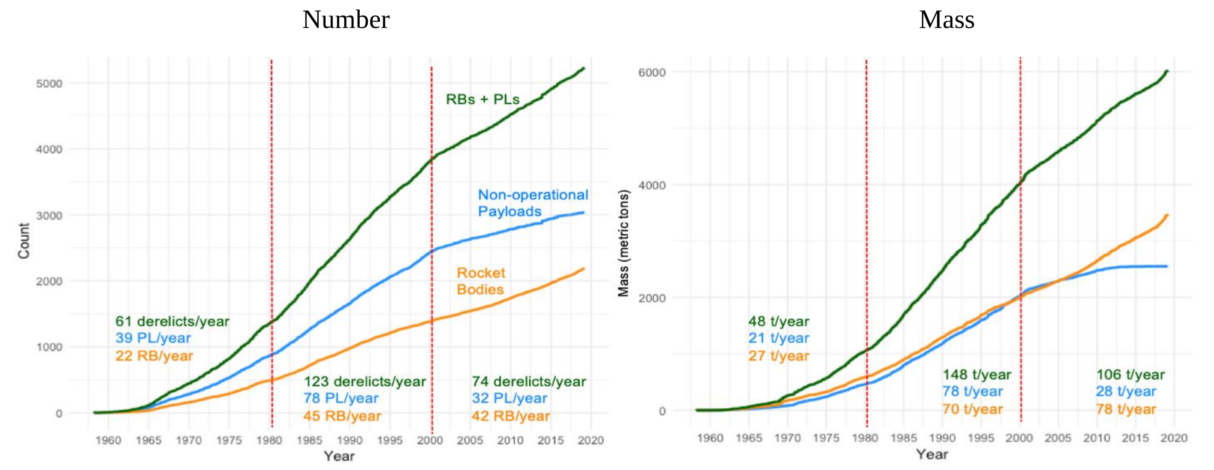

Figure 1. Accumulation of massive derelicts in Earth orbit show a constant increase in both number and mass.

Figure 1 also shows an emergence of three “eras” in the progression of derelict accumulation. Except for an exponential trend as the Space Age started, the Exploration Era of the Space Age (i.e., 1957-1980) had an overall linear growth rate of the current population: ~39 PLs per year and ~22 RBs per year, for a total of 61 intact derelicts per year. By mass, the accumulation was 21, 27, and 48 metric tons per year for PLs, RBs, and combined intact derelicts, respectively. The second era of the Space Age, Maturation (1980-2000), contributed the most to the current population of intact derelicts. PLs and RBs accumulated at a rate of 78 and 45 per year, respectively, while their masses accumulated at 78 and 70 metric tons per year. As a result, 49% of the total intact derelict mass currently in orbit originated from launches in this time frame. In the final era, Diversification, from 2000 to present, the mass growth rate of 148 metric tons/year in Era Two slowed down to 106 metric tons/year. Derelict accumulation by number is also substantially slower during the Diversification Era, at around 32 non-operational PLs/year and 42 RBs/year (74 derelicts/year). This is partially due to fewer launches, smaller spacecraft in LEO, greater adherence to debris mitigation guidelines, and since many of the PLs launched in this era are still operational.

2 Orbit Class Definitions

While examining the accumulation of massive derelicts and assessing when they were abandoned is noteworthy, characterizing where (i.e., which orbits) these intact derelicts currently reside provides specific information needed to determine their debris-generating risk. The intact derelicts are partitioned into nine orbital categories as depicted in Figure 2. Low Earth Orbit (LEO) consists of three families: LEO LOW with orbits below 650 km [A]; LEO HIGH with orbits completely contained within 650-2,000 km [B]; and LEO OTHER with perigees below 650 km and apogees between 650-2,000 km [C].

Semi-synchronous orbits (SEMI) span 18,000-24,000 km [D] while SEMI Transfer Orbit (STO) objects have perigees in LEO and apogees in SEMI [E]. Geosynchronous orbit (GEO) spans 35,786 ± 200 km [F] while GEO transfer orbit (GTO) objects have perigees in LEO and apogees in GEO [G]. Lastly, High Transfer Orbit (HTO) objects [H] have perigees in LEO and apogees between 2,000 km and 40,000 km (but not in either SEMI or GEO). Any objects that are in Earth orbit but are not included in any of these categories are considered to be in the Other category.

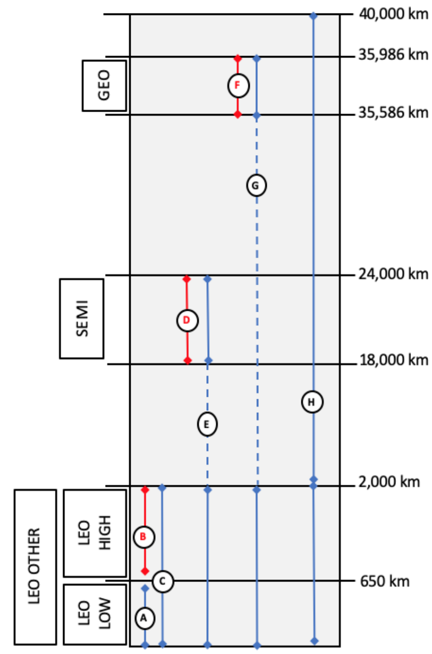

Figure 2. Nine orbit families are used to assess the accumulation of massive intact derelicts.

The focus of this study is on four "circular" groupings (LEO LOW, LEO HIGH, SEMI, and GEO) because they are popular regions for space missions and have significant orbital lifetimes except for LEO LOW. Due to its shorter orbital lifetimes (maximum of 25 yr), LEO LOW had originally been discounted as a significant region of concern, but due to its popularity (especially over the last 10 years) this study will test this assumption. All of the transfer orbits pose a unique potential cross-contamination hazard between LEO (the most densely populated region in Earth orbit) and higher operational orbits that have significantly fewer debris objects. However, collisions that occur between the objects in transfer orbits and objects in LEO may create debris that can pose collision hazards to objects in the higher SEMI and GEO regions that have been seen as largely unaffected by debris growth in LEO.

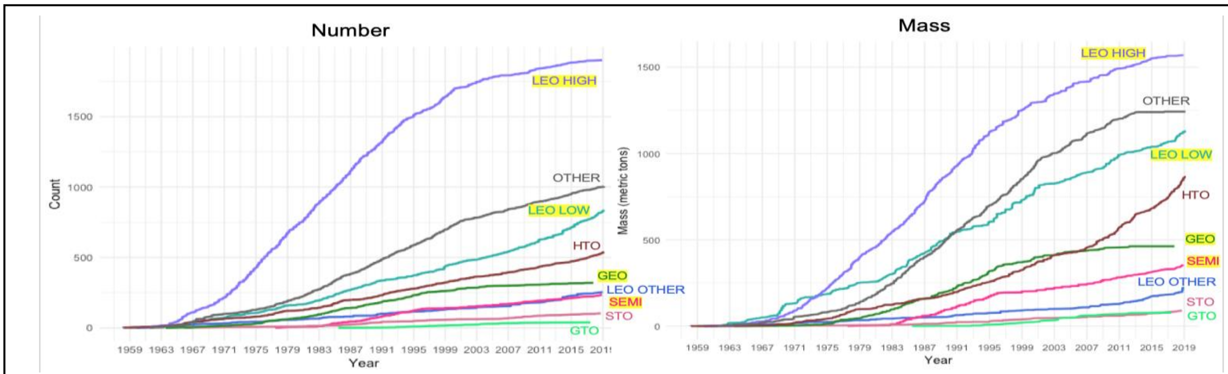

Figure 3. Accumulation of massive derelicts by nine orbit families show that most of the derelicts are in LEO.

This study will examine where, when, and by whom these massive intact derelicts have been deposited to investigate the importance and characteristics of the distribution of these objects to determine the concentration points in Earth orbit that need to be scrutinized to best manage the risk of potentially massive debris-generating collisions. Previously, clusters of objects in LEO HIGH have been monitored and characterized; the assumptions as to the criticality of these clusters will be challenged and the need for any additional cluster(s) will be investigated.

3 Accumulation by Orbit Type

Examining the distribution of the intact derelict objects by orbit type, the LEO HIGH region stands out as a significant pool for abandoned mass; ~2,000 intact derelicts comprising over 1.5M kg of mass reside in an altitude span of 1,350 km. Figure 3 shows the accumulation for all orbit classes. The next highest region is "Other" which spans an enormous volume (basically most of the space between LEO and GEO) and is not concentrated in any way.

LEO LOW is the next most littered region of space with ~830 objects (amounting to about 1M kg of mass) in orbit. The good news is that objects in LEO LOW will likely have orbital lifetimes less than ~25 years; however, at the same time, manned space missions and many new operational satellites are being deployed to LEO LOW. As a matter of fact, of the estimated ~2,000 operational satellites in Earth orbit, ~760 reside in LEO LOW; this is a major increase as there were only about 140 operational satellites in LEO LOW in 2015 out of a total ~1,000 operational satellites.

The next largest contributor by number and mass is the HTO family of objects (i.e., perigee in LEO and apogee somewhere above LEO). These objects spend only a short time in LEO and do not have an apogee in either Semi-Synch or GEO so they do not pose a specific high probability concern.The next two families of intact derelicts are for GEO and SEMI. There are 320 intact derelicts in and around GEO (only 400 km altitude span) comprising over 460,000 kg of mass. The 236 intact derelicts in SEMI reside in the wide swath (6,000 km altitude span) which contains over 350,000 kg. There are prescribed altitude bins within this SEMI region where specific Positioning, Navigation, and Timing (PNT) systems operate: Galileo: 23,522/23,922 km, Beidou: 21,232/21,832 km, GPS: 20,482/19,882 km, and GLONASS: 18,830/19,430 km.

The ~250 objects in LEO OTHER account for over 200,000 kg. These objects pass by objects in both LEO LOW and LEO HIGH on a regular basis, but due to their more elliptical orbits, their collision risk is spread across a larger (up to ~1700 km) altitude span. This is still much smaller in volume than the SEMI region. The last two groupings by number and mass should not be overlooked. There are only 39 objects in GTO that amount to ~80,000 kg of mass while STO contains ~100 intact derelicts amounting to ~90,000 kg of mass. When intact derelicts in these orbits were scrutinized in 2018 [1], a PSLV (Indian) STO RB was identified as the statistically most-concerning object in STO or GTO. Two months after this declaration of its risky orbit, the PSLV STO RB (SATNO 40270) had a conjunction of less than 35 m with an intact derelict PL at 600 km; this event had a CSpOC-announced probability of collision of 12%! [See www.Space-track.org announcement on 28DEC2018].

Table 1 provides an executive summary of the approximate volume and composition of each of the orbit classes. It is worth noting that the consequence of a collision between derelicts will be greater for orbits containing more operational payloads since the resulting debris would pose a collision hazard to a greater number of functioning satellites. All orbit classes contain more derelicts than operational payloads, except for GEO, which contains ~1.5 times more operational payloads than derelicts. LEO LOW contains ~1.2 derelicts for every operational payload, while LEO HIGH contains ~4.5.

Table 1. Characteristics of the orbit classes highlight the unique debris-generating hazards in the LEO regime as of 1 June 2019. It is notable that LEO LOW has both the most derelict mass per volume and the number of operational payloads.

Orbit Class	Volume (10^{12} km^3)	# Derelicts	Mass (metric ton)	# per 10^{12} km^3	Mass per km^3 (kg)	# of Op PLs	Op-PLs per 10^{12} km^3
LEO LOW	0.3	833	1,130	2,777	3,777	~760	2,543
LEO HIGH	1	1,900	1,570	1,900	1,570	~410	410
LEO OTHER	1.3	254	223	181	159	~80	55
SEMI	51	236	356	4.6	7.9	~110	2.12
STO	86	103	90	1.2	1.0	1	0.01
GEO	3	320	462	110	159	~500	173
GTO	82	39	78	0.5	1.0	0	0
HTO	90	537	865	6	9.6	~15	0.14
Other	~1,000,000	~1,000	1,243	0.001	0.001	~60	0.0001

Since the three LEO classes occupy a small volume compared to higher orbits, they have notably higher spatial densities. The volume of the three LEO classes combined is about one-third the volume of GEO (~1E12 vs. ~3E12 km^3). For every 10^{12} km^3 in volume, the three LEO classes combined contain ~2,300 derelicts while GEO contains ~110 and SEMI contains ~5. This observation, in combination with the much greater relative velocities at LEO altitudes, accentuates the debris-generating risk in the LEO classes vs GEO or SEMI. This observation builds the justification for examining clusters of even more concentrated risk in LEO as per a continuing Massive Collision Monitoring Activity (MCMA). [1, 2]

4 Examining System Deployments and Orbital Decays

By considering both system deployments as well as orbital decays, the dynamics of the orbits being examined become more clear; Figure 4 shows some key non-LEO orbits. The solid lines show deployments while the dashed lines represent when objects re-enter Earth's atmosphere (i.e. orbital decays). There is reason to be concerned not only because derelicts are accumulating, but because some are accumulating in certain regions at faster rates than others. No derelicts in SEMI or GEO have decayed yet; 11 out of 50 (22%) have decayed from GTO, and 8 out of 111 (7%) have decayed from STO. This finding highlights the longevity/persistence of derelicts in GEO and SEMI as compared to their elliptical counterparts.

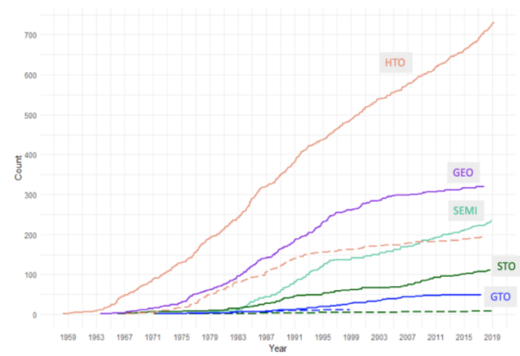

Figure 4. Examining system deployments and orbital decays in key orbits show that transfer orbits are very dynamic.

Figure 5 shows the accumulation of derelicts over time in the three LEO classes based on when derelicts were deployed (solid line) and when they re-entered (dashed line). Although LEO LOW has the fastest accumulation of deployments, it also has the fastest decay rate. This observation is expected due to the increased effects of drag at lower altitudes. However, there is still a net increase, as shown previously. On the other hand, the decay rate in LEO HIGH is lower than it is in both LEO LOW and LEO OTHER, meaning that derelicts that are deployed in this region rarely re-enter Earth's atmosphere. In reality, derelicts in LEO HIGH do not decay directly, they move into LEO LOW which looks like a "deployment" to LEO LOW. In LEO OTHER, the deployment rate is relatively lower and the decay rate is about comparable to LEO HIGH, meaning that the net increase is not as large as LEO HIGH. When atmospheric drag acts upon the low perigees of LEO OTHER objects, these derelicts may "decay" into LEO LOW before re-entering the atmosphere. These findings help clarify why the risk in LEO HIGH is greater than in the other two LEO classes.

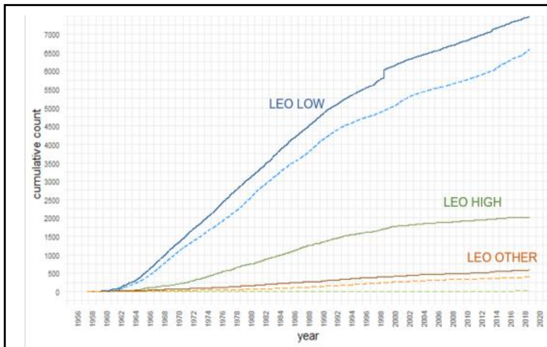

Figure 5. Accumulation rates of derelict objects by number are very different for the LEO orbits examined

5 Accumulation Over Time in Three Circular Long-Lived Orbits

Figure 6 shows the breakdown between eras in which the derelicts currently in orbit were deployed into space. The left column shows the number of derelicts while the right column shows the total mass of derelicts (in metric tons). Across the three circular long-lived orbit classes, Era Two (Maturation) is the prominent contributor (except for SEMI RBs), accounting for 45% of RBs and 56% of PLs. For both RBs and PLs, Era One (Exploration) uniquely accounts for more number than mass (~32% of derelicts, ~20% of mass), implying that derelicts from the later two eras are more massive than those from Era One. Intact derelicts are, on average, getting more massive over time, while operational PLs in LEO are getting less massive. Of these three circular orbit classes, LEO HIGH has the largest proportion of old derelicts – about a quarter of the mass (and 40% by count) of both RBs and PLs in LEO HIGH were deposited in Era One. Close to half of both RBs and PLs were deposited during Era Two. Even though there are around twice the number of PLs as RBs, there is ~200 more tons of mass from RBs than PLs. The proportion of derelicts from Era Two is ~7% higher in PLs than in RBs. LEO HIGH also has the smallest proportion of derelicts deposited in Era Three; only ~11% of derelicts (14% of RBs and 10% of PLs) are from this most recent era.

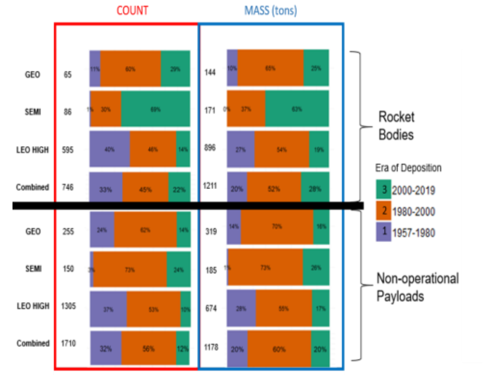

Figure 6. Accumulation over time highlights the importance of the 1980-2000 timeframe.

There were few derelicts (five PLs and one RB) deployed into SEMI in Era One, meaning that it is a “newer” orbit. In fact, SEMI is the only orbit with most mass and number deposited in the last twenty years. Around 73% of PLs were deployed in Era Two and around 24% in Era Three, while the opposite is true for rocket bodies – around 30% were deployed in Era Two and about 60% since 2000. From Era Two, there are 110 PLs and 27 RBs (~4 times more PLs than RBs), while from the most recent era, there are 33 PLs and 58 RBs (~2 times more RBs than PLs). This ratio could imply either (1) multiple payloads are deployed by a single RB more now than before (this is true) or (2) many payloads deployed since 2000 are still operational and thus excluded from this analysis (this is also true).

In GEO, 11% of RBs and 24% of PLs were deposited from 1957-1980. There are 59 PLs and 8 RBs deposited in Era One (about 7 times more PLs than RBs), but in Era Three, there are 30 PLs and 18 RBs (about 2 times more PLs than RBs). This ratio could imply one of the same two things as listed above for SEMI but also that many times the apogee kick motor stays attached to the PL in GEO. With respect to RBs in GEO, 11% are from Era One and 29% are from Era Three. Conversely, there are more PLs total, but 24% are from Era One and 14% are from Era Three. This implies that there are ~2.5 more PLs than RBs from Era One, whereas the most recent era contributed ~2.5 more RBs than PLs. However, any accounting of ratios for RBs and PLs from the last era must consider the fact that many of these payloads are still functioning.

6 Country Contributions: Three Circular Orbits

Figure 7 shows which countries are responsible for deployments of massive derelicts currently in orbit, across the three long-lived circular orbits. Of the ~2,400 derelicts currently in one of these three orbit classes, the top five contributors are Russia[1] (66%), US (22.5%), China (3%), Japan (1.5%), and India (1.1%). All remaining contributors are responsible for less than 1% of derelicts.

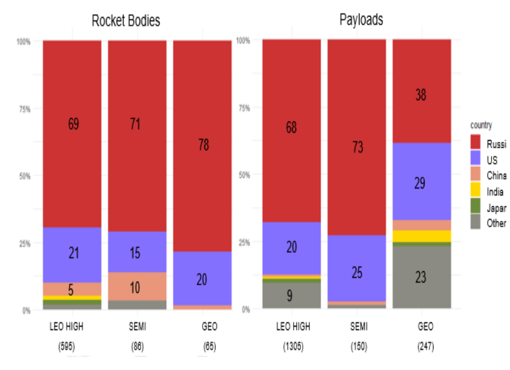

Figure 7. Accumulation by country in the three circular long-lived orbits shows Russia as the primary contributor.

Russia was responsible for the largest percentage of RBs in each of the three circular orbit classes. The contributors to rocket bodies in LEO HIGH are Russia (69%), US (21%), China (5%), Japan (1.8%), France (1.5%), India (1.5%), and Ukraine (0.3%). The contributors to RBs in SEMI are Russia (71%), US (15%),

[1] Russia is used to represent the Commonwealth of Independent States (CIS) which actually includes 12 states: Armenia, Azerbaijan, Belarus, Georgia, Kazakhstan, Kyrgyzstan, Moldova, Russia, Tajikistan, Turkmenistan, Ukraine, and Uzbekistan.

China (10%), and France (3.5%). There are no other contributors to GEO RBs besides Russia (78%), US (20%), and China (2%); the large number of international payloads deployed to GEO were transported by Russian, European, American, Indian, and Chinese launch vehicles; many of the RBs used end up in transfer orbits. PL contributions are more diverse than RB contributions. Russia was responsible for the largest percentage of RBs in LEO HIGH and SEMI, but only 38% in GEO. The US is responsible for 20%, 25%, and 29% of PLs in LEO HIGH, SEMI, and GEO, respectively. In SEMI, there are no other contributors to PLs besides Russia (73%), US (25%), China (1%), and the European Space Agency (ESA, 1%). In both LEO HIGH and GEO, there is a significant portion of PLs originating from “other” countries.

7 Debris-Generating Risk: Three Circular Orbits

The pace of satellite deployments is increasing as more countries become capable of manufacturing and operating satellites; more multi-payload deployment launch options; and more/larger constellations are being deployed. However, these operational satellites will be competing for space with a population of intact massive derelict objects (abandoned RBs and non-operational PLs) in orbit. While an operational spacecraft can typically maneuver itself out of harm’s way, the derelict objects, which are hundreds to thousands of kilograms in mass each, cannot. We know that collisions between massive satellites may have significant consequence if—when—they happen. Rather than dealing with the consequence of a collision between derelict objects once it occurs, the space community should be preventing catastrophic collisions from occurring in the first place. Collision risk is the product of probability and consequence. Probability of collision is proportional to the spatial density of the objects, i.e. number/km^3, which characterizes how densely populated a region is. The primary metric for consequence is average mass per derelict since the amount of mass involved in a collision determines how many debris fragments would likely be produced, both trackable and, even worse, LNT. This assumes a hypervelocity (> 6 km/s) collision; over 85% of recorded conjunctions in LEO have relative velocities that exceed this threshold. While it is feasible to monitor and act upon potential collisions between the trackable debris population, LNT debris pose a greater risk due to the difficulty of taking action to predict or avoid collisions with them while still capable of terminating a satellite’s mission.

There exists a tradeoff when deciding which objects to monitor and characterize: analyzing more objects is more complete but less conducive to initiating action. While collisions involving less massive derelicts are possible, they do not evoke the same sense of urgency that more massive collisions do. The following analysis considers only derelicts greater than 700 kg in order to limit the scope to only the highest-consequence collisions. In addition, the original motivation for choosing a subset of objects to monitor was to reduce the computational resources needed in conjunction screening. By limiting the analysis to only massive derelicts within tight clusters, the number of computations is reduced from ~10 million (for an all-on-all comparison of the entire satellite catalog) to ~300 thousand. While any choice of where to draw the cut off line is somewhat arbitrary, it is necessary to do so to strike a balance between completeness and practicality.

Figure 8 shows risk and its two components (spatial density and average mass) plotted across all altitudes, which identifies pockets of high debris-generating risk in LEO. Of the ~3,000 intact derelicts with mass greater than 700 kg in Earth orbit, over 80% are in LEO. So, it is not surprising that the spatial density in LEO is also higher than any other region by at least a factor of 14 (over GEO) but the average mass in LEO is smaller than in GEO. This results in the risk in LEO, on average, being nearly ten times that in GEO and over 120 times higher than SEMI. Since the risk is greatest in LEO, it is prudent to take a closer look in that region. However, the massive derelicts, and therefore the risk, are not evenly distributed throughout LEO. Figure 9 zooms in to plot the spatial density of massive intact derelicts, average mass, and debris-generating risk in LEO as a function of altitude. Several distinctive peaks emerge, centered at 775, 850, 975, 1200, and 1500 km. These five peaks correspond to existing clusters being monitored via MCMA. However, the bi-modal peak spanning 450 - 650 km is not currently being monitored but poses a significant risk.

As Figure 9 demonstrates, the two primary peaks at 850 km and 975 km (clusters C850 and C975) clearly have the greatest consequence (i.e., greatest average mass) and greatest probability (i.e., spatial density), respectively. Each of the other clusters (C775, C1200, and C1500) also has unique characteristics; to understand their uniqueness, two additional factors that amplify the consequence of a potential collision must be explained: debris persistence and number of operational satellites nearby. Generally speaking, as altitude increases, the effects of atmospheric drag decrease exponentially, meaning orbital lifetimes are exponentially longer. This observation is what makes the derelicts at the high altitudes of C1200 and C1500 uniquely risky—although derelicts are fairly sparsely packed in these zones, debris produced from a collision involving these massive objects would persist in orbit much longer than debris from a comparable collision at a lower altitude. C775 has formed in a region that also contains many operational satellites, which means that any debris produced in this cluster poses a threat to more operational satellites than in any of the original clusters.

Figure 10 overlays the distribution of operational satellites (green curve) and the logarithmic persistence of orbital lifetime (orange line) on the risk plot (red curve). It is informative to investigate why the overlap of massive derelicts and operational payloads (seen ~450 - 650 km and ~775 km) happened. Most national and international

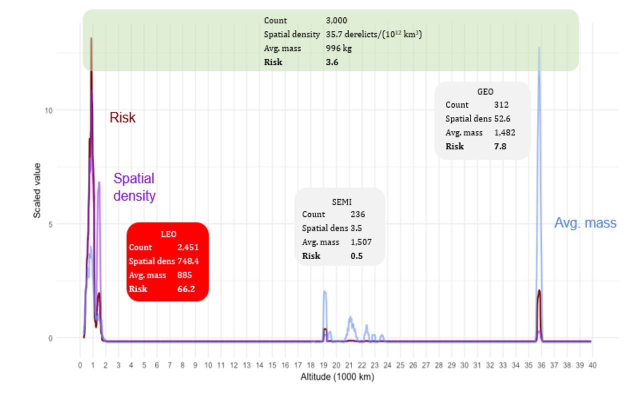

Figure 8. The number of derelicts, spatial density, average mass, and debris-generating risk for massive intact derelicts for LEO, SEMI, and GEO are depicted as a function of altitude.

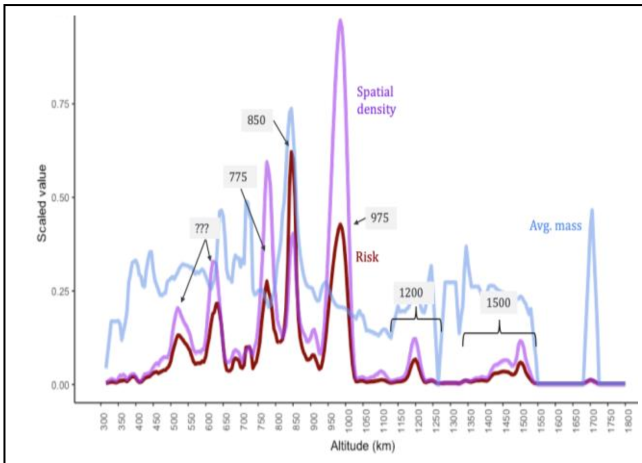

Figure 9. A closer examination of the risk contours in LEO show several clear clusters of intact derelicts.

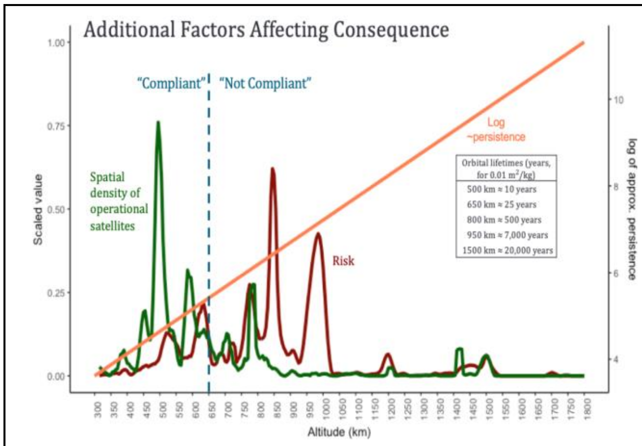

Figure 10. Persistence of debris and proximity to operational satellites are two important additional components of consequence that act as opposing forces in LEO.

debris mitigation guidelines recommend that a space object should be removed from orbit within 25 yr after its mission is completed (i.e., 25-year rule). This threshold can be met naturally by placing the system below 615 to 650 km. [3] If satellite operators want to deploy above this altitude, applicants must demonstrate an ability to move the object to the lower orbit later such that it re-enters no later than 25 years hence. Interestingly, before 2000, only ~3% of payloads were deployed between 450 and 750 km, while from 2000 to present, ~25% of payloads have been deployed in this small sliver of LEO.

The potential unintended negative consequence of the 25-year rule will only continue to grow as more satellites are deployed in this region and as other higher altitude objects either drift down due to the effects of drag or are maneuvered there to meet the 25-year rule. Amazon’s Project Kuiper is planning to deploy a constellation of ~3,000 satellites to LEO, split between 590, 610, and 630 km altitude orbits. While Project Kuiper may have selected the orbits carefully to provide “low-latency, high-speed broadband connectivity to unserved and underserved communities around the world,” [4] there is emerging debris-generating risk at the exact altitudes where they are deploying, which may come as an unwelcome surprise. The 25-year rule is also what led MCMA to initially exclude intact derelicts below ~650 km. MCMA began by selecting “pure” clusters (aka version 0.0) which comprised of only Russian paired rocket bodies and payloads. While the clusters included some derelicts below the 700 kg threshold, Figure 11 displays the risk associated with derelicts that are both in the “pure” clusters and at least 700 kg in mass. For example, C775 contained 88 derelicts, but only the 74, which are at least 700 kg, are depicted in the plot.

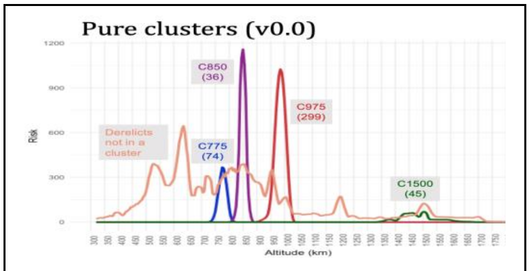

Figure 11. The debris-generating risk in the four "pure" clusters are plotted against the risk from derelicts not included the clusters.

Figure 12 shows the “complete” version of the clusters that were being monitored (up to 1OCT2019) for conjunction activity. These clusters (version 1.0) were formed by (1) adding a new cluster at 1200 km, (2) “completing” the clusters by adding derelicts greater than 1,000 kg that resided within the altitude span of the “pure” clusters, and (3) creating a new cluster (cleo) to include derelicts whose orbital altitudes cross between cluster boundaries. The goal is to leave as little risk unmonitored as possible in order to more accurately characterize the conjunction behavior.

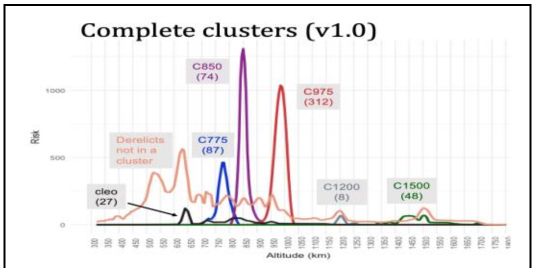

Figure 12. The number of derelicts not included in MCMA dropped moderately with the “complete” clusters.

Figure 13 shows the new MCMA clusters (as of 1OCT2019) with a new cluster (C615) that has peaks at 525 km and 625 km. Version 2.0 of the clusters also expanded the altitude span of C775 to include the risk peak around 700 km, and included all objects with mass greater than 700 kg into each existing cluster altitude span. The massive derelicts not in a cluster (and thus not being monitored) are almost non-existent with this last configuration. The new cluster (C615) has a bi-modal distribution of derelicts: one peak is centered at ~625 km and a smaller one at ~525 km. Since this altitude region experiences moderate effects of drag, the cluster membership will be more dynamic. C615 is potentially both a result of and a concern for the growing number of satellites deployed in this altitude range. This analysis validates the significant debris-generating risk of the pre-study MCMA clusters and notes that one significant cluster has been ignored until now; C615 is now contained within MCMA.

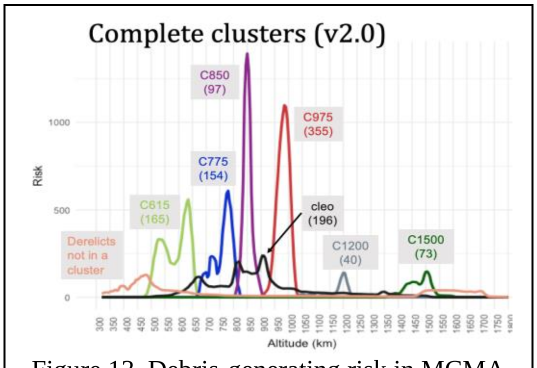

Figure 13. Debris-generating risk in MCMA is now captured in six LEO clusters.

Table 2 shows the new MCMA with over 2.3M kg of derelict mass in nearly 1,300 objects monitored daily. C975 still has the greatest probability of a collision event but C850 has a slightly greater overall risk. The new C615 cluster is about the middle of the pack from a simple risk perspective but as shown in Figure 10, a collision in C615 will likely affect more operational satellites than any other cluster. The collision rate parameter is very interesting when considered in context to the expected explosion rate of abandoned rocket bodies; an accidental explosion is estimated to occur at a rate of 2×10^{-4} per year (i.e., 1/5000). [5] However, the collision rate within the six primary clusters all exceed this number.

Table 2. MCMA now includes ~1,200 objects comprising over 2.3M kg of mass.

Cluster	#	Total Mass (kg)	Ave Mass (kg)	Span (km)	Spatial Density, (#/km^3)	"Risk": Ave Mass x SPD	Ave. Collision Rate/yr
C615	165	304,764	1847	369	0.147	272	~1/1,000
C775	154	242,407	1574	246	0.167	263	~1/400
C850	97	316,019	3258	201	0.174	567	~1/800
C975	355	417,618	1176	199	0.438	515	~1/90
C1200	40	55,905	1398	255	0.019	26	~1/10,000
C1500	73	95,730	1311	206	0.037	48	~1/1,500
cleo	196	350,462	1788	1,700			
chigh	189	572,814	3031	40,000			
TOTAL	**1269**	**2,355,720**					
AVE			1923				

8 Summary

The study of intact derelicts in Earth orbit have provided three key observations:

1. Add a Cluster: The accumulation of massive derelicts between 450 to 650 km (i.e., C615) has been identified as being significant. While previously-selected clusters have been shown to be largely populated by paired RBs and PLs of Russian origin and then augmented by other objects, the newly characterized C615 contains very few paired RBs/PLs but contains a greater amount of debris-generating risk than some of the original clusters.
2. Age: Clusters that pose the greatest debris-generating risk are decades old, largely deposited between 1980 to 2000. C615 is the exception; 25% of its members were added since 2000. This is the largest percentage of any of the clusters from the last twenty years by more than a factor of two.
3. Origin: Russia is the worst offender for abandoned derelict hardware for all orbits. Yet, the Chinese and Indian activities are beginning to contribute to the debris-generating potential in certain orbits. China has "contributed" 41% of total RBs over the last five years in the three vital orbits (LEO, SEMI, and GEO). Despite Russia's dominance of LEO HIGH, China has been the primary contributor of derelict hardware into LEO HIGH in seven of the last nine years. China also left eight RBs in SEMI in 2018 alone, amounting to 9% of the total abandoned RBs in this region over the Space Age. Indian launches have left eight RBs in LEO HIGH orbits over the last eight years from only 16 LEO HIGH launches.

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