UPDATING THE MASSIVE COLLISION MONITORING ACTIVITY - CREATING A LEO COLLISION RISK CONTINUUM

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ABSTRACT

Since 2014, the Massive Collision Monitoring Activity (MCMA) has monitored and characterized the encounter dynamics of massive derelict objects in low Earth orbit (LEO). This activity identified critical clusters of high debris-generating potential. However, the constant evolution of the debris environment highlights the need for a more flexible approach to identifying the objects that pose the greatest debris-generating potential in LEO. This debris evolution is due to continuing abandonment of massive derelicts in orbit, changing altitudes of these massive derelicts due to atmospheric drag, rapid deployment of satellite constellations, and identification of many new objects in orbit with the development of new space situational awareness capabilities. A collision risk continuum updates the statistically-most-concerning (SMC) objects based on potential conjunctions. Every object in the LeoLabs satellite catalog is assigned a mass, then conjunctions among all the objects are monitored and characterized. The probability of collision for each conjunction is multiplied by the mass of the objects involved in that conjunction to determine the debris-generating risk for each encounter. This analysis is used to identify (1) the objects that are most likely to contribute to future debris growth in LEO, and (2) the regions in LEO that have the highest risk of debris-generating events.

1 BACKGROUND

One of the authors has been working for over six years to monitor and characterize the clusters of massive derelict objects in Earth orbit and their debris-generating potential. [1-3] These large, intact objects have accumulated in several clusters in low Earth orbit (LEO) as depicted by Fig. 1 and detailed in Tab. 1.

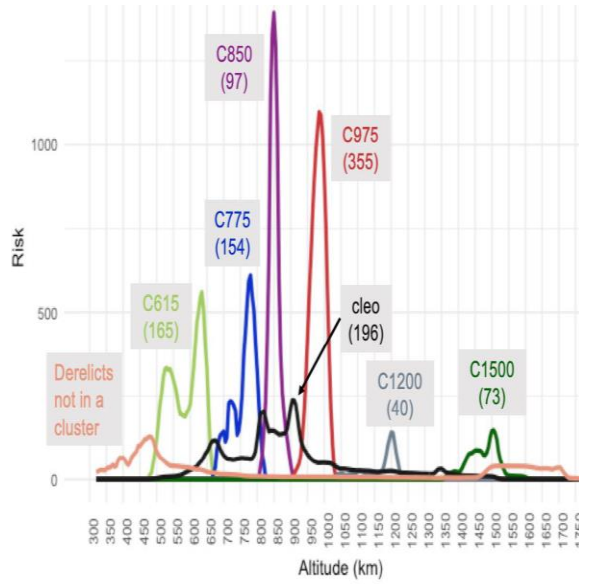

Figure 1. MCMA has monitored over 1,200 abandoned, intact objects in LEO for over six years.

Cluster	#	Total Mass (kg)	Ave Mass (kg)	Span (km)	Spatial Density, SPD (#/km^3)	Peak "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				

Table 1. The MCMA clusters comprise over 2,000,000 kg of derelict hardware in LEO, from a variety of countries.

The purpose of the Massive Collision Monitoring Activity (MCMA) is to identify the objects that present the greatest risk for the growth of orbital debris and increase of the collision hazard. The greatest concern is not having large objects collide with operational satellites; rather, the greatest concern is having two of these massive objects collide with each other. Such a

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collision will create large amounts of debris that pose a lethal collision hazard to operational satellites. Identifying these massive derelict objects provides a list of prime candidates for debris remediation.

In 2019, during the International Astronautical Congress (IAC) in Washington, DC, a question was asked: "what are the top 50 objects that need to be removed from LEO?" Fig. 2 presents a summary of a year-long research and analysis effort by 19 international debris experts from 13 countries and entities. [4-12] This subset of intact derelict rocket bodies (R/Bs) and defunct payloads (PLs) provides insight into the objects and regions that are likely to fuel the growth of the debris population.

Most of the objects are Soviet/Russian R/Bs deployed before 2000. The four most important metrics for inclusion are mass and size of the object, its probability of collision (PoC) with another massive derelict, persistence of debris, and proximity to operational satellites. This highlights the difficulty in accurately (1) depicting which objects are the most important to remediate to reduce the growth of orbital debris, and (2) characterizing the benefit of remediating these objects. The PoC is driven by stochastic conjunction dynamics. As described in the referenced paper, remediation may include removal of an object from orbit, moving it to a different (*e.g.*, less cluttered) orbit, or simply ensuring that a collision between the massive objects does not occur (*i.e.*, "remediate in orbit").

However, considering only close approaches of the "top 50" objects to determine debris-generating risk is insufficient. The authors rather suggest considering potential collisions among all objects in LEO – the LEO Collision Risk Continuum (LRC). The LRC was inspired by the 2019 paper that introduced the Global Risk Continuum (GRC) depicted in Fig. 3. [13] The unique data generated by LeoLabs is applied to the conjunction dynamics of all objects in LEO, using the LRC to depict the debris-generating potential in LEO.

2 MOTIVATION

On May 21, 2019, an 8,900 kg SL-16 R/B and a 3,250 defunct ELINT PL at 850 km passed within 87 m of each other, with a relative velocity of ~14 km/s. This conjunction was derived from the Combined Space Operations Center (CSpOC) special perturbations ephemeris, and the PoC was calculated to be ~1/1000. If this collision had taken place, it would likely have created ~12,000-15,000 cataloged fragments, doubling

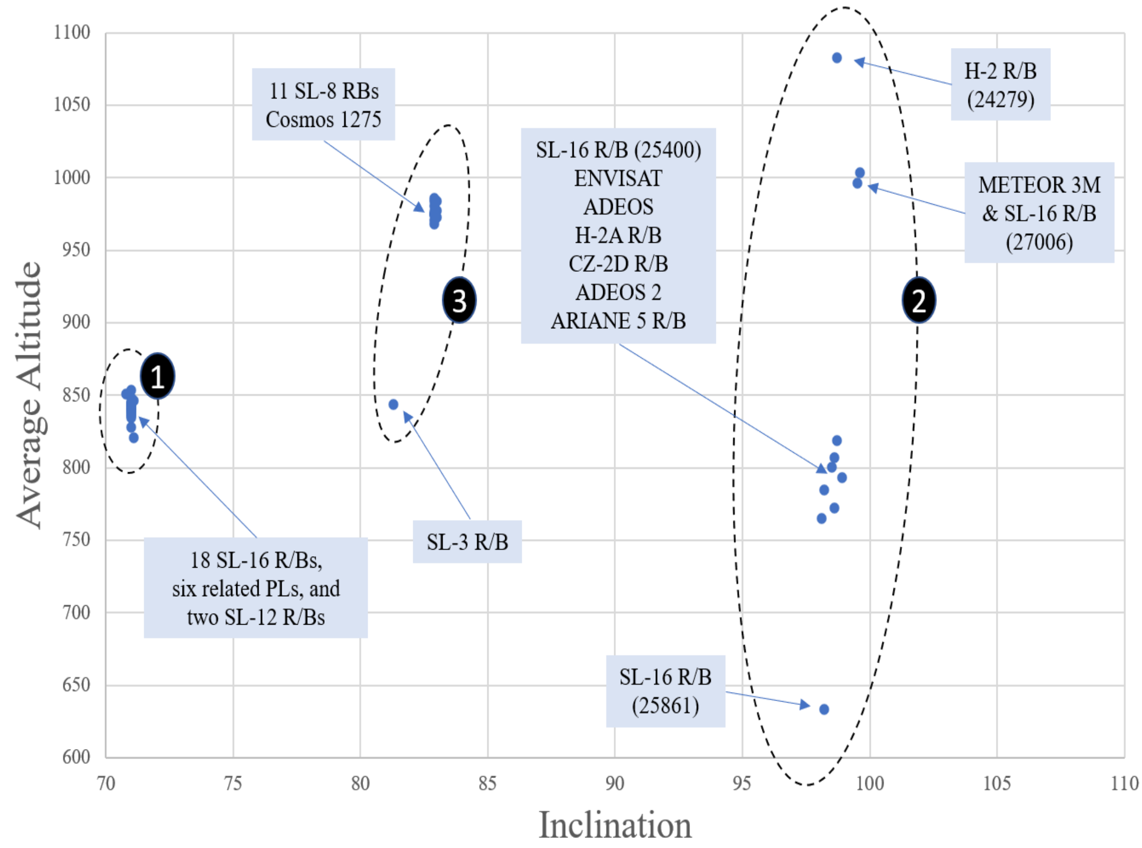

Figure 2. The top 50 statistically-most-concerning objects in LEO are largely within three groups; the two largest groups are Cluster 850 (ellipse 1) from the MCMA, and massive derelicts in sun-synchronous orbit (ellipse 2). [12]

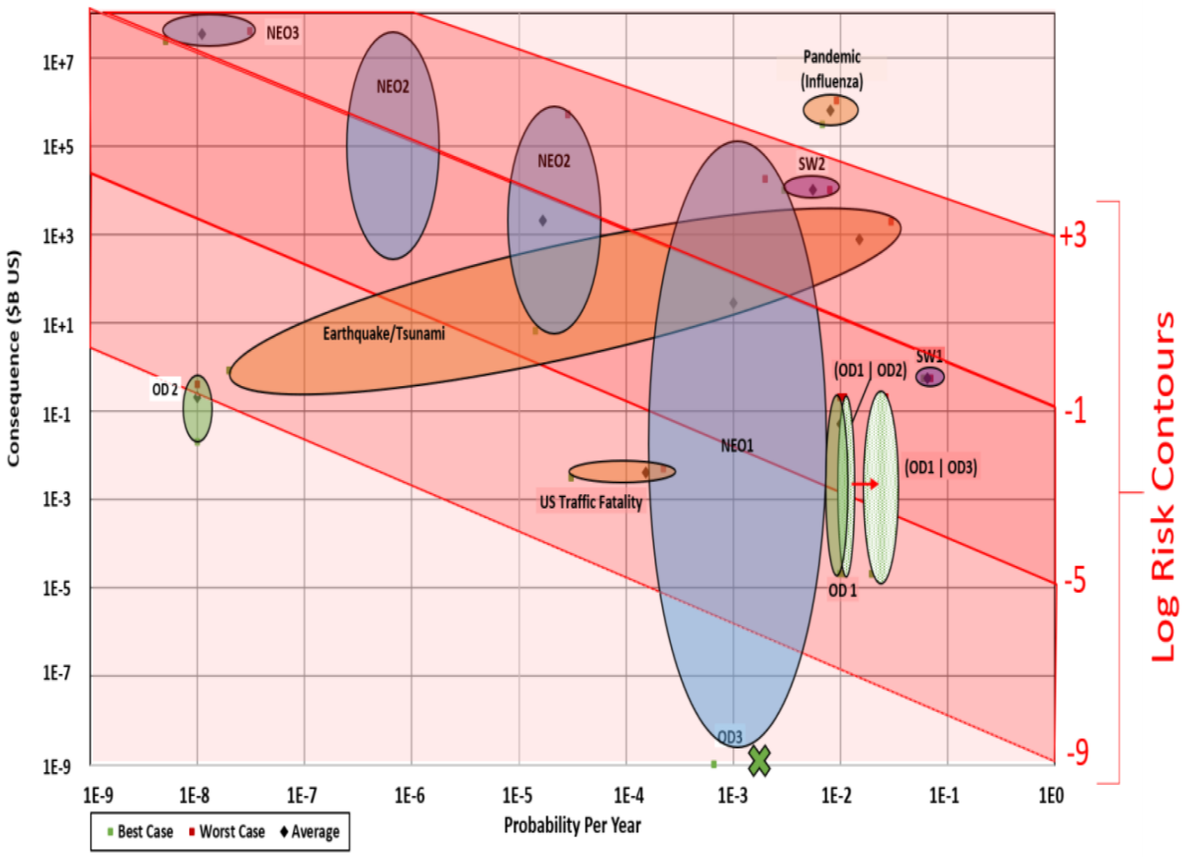

Figure 3. The GRC plot depicts the risk from hazards to mankind based on its annual probability of occurring and immediate impact (i.e., consequence) in terms of US dollars.

the LEO catalog population.

Further, on December 27, 2019, the 18th Space Control Squadron (18 SPCS) at CSpOC posted a close approach prediction for the following day between an abandoned Indian R/B (40270 / L6849[1]) and an unidentified defunct US payload. The PoC was estimated to be 12%, and the combined mass of the two objects exceeded the mass of the Fengyun 1C whose fragmentation contributed over 3,000 cataloged fragments to LEO in 2007.

In January 2020, LeoLabs identified a close approach between two small non-operational PLs, IRAS and GGES4. [14] The combination of the high altitude of the event (907 km), the mass involved (~1,200 kg), the high relative velocity (14.67 km/s), and a PoC of ~1% made this a troubling event.

Late in 2020, LeoLabs again monitored and characterized a close approach on October 16, 2020, between two intact objects – Cosmos 2004, a derelict Russian PL, and an abandoned Chinese CZ-4C R/B. The combined mass of the two objects was 2,800 kg with a predicted PoC of ~9% [15]. With a closing velocity of over 14 km/s, a collision between these two objects could have produced ~5,000 trackable fragments centered at ~990 km, so the debris would have been very long-lived.

The LEO environment has witnessed a doubling of operational satellites in the last 18 months, rideshare launches with large numbers of satellite deployments, and poor debris mitigation guideline compliance in LEO, among other concerns.

The four events described above, combined with the other indications of an increasingly cluttered LEO environment, motivated the authors to create an enduring analytic perspective to quantify the "heartbeat of the LEO ecosystem" by statistically characterizing potential hotspots of future debris generation.

The real-time, automated, deterministic collision avoidance support that LeoLabs provides to LEO operators integrates well with this approach.

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[1] Objects in the LeoLabs' satellite catalog are assigned an L-number that corresponds to objects in the space-track.org catalog.

3 TECHNICAL APPROACH

The LRC is generated with the following definitions and assumptions:

- The probability of collision (PoC) for each event is taken from the LeoLabs data platform. All conjunctions with a PoC > 1E-6 are used.
- The consequence for each event is the total mass of the objects (in kg) involved in a potential collision. This is a surrogate for the amount of debris that would likely be produced if a collision occurs.
- The risk is simply the product of the probability of collision (PoC) and consequence (mass). This “risk” has units of kg and is proportional to the projected number of debris fragments.
- There are two families of conjunctions plotted: (1) operational payloads (OPL) against all objects (OPL-ALL), (this includes other OPLs and debris (DEB), which are fragments from collisions and breakups (FRAG) and intact massive derelict (MD) rocket bodies (R/B) and payloads (PL)) and (2) collisions between two DEB (DEB-DEB). For this exercise, the LeoLabs catalog had ~15,000 objects, of which ~2,400 were OPL as of January 1, 2021.
- The resulting risk values are plotted with equal risk contours to differentiate the groupings of conjunctions.
- The risk values for all conjunctions are then plotted as a function of altitude, for perspective.
- Finally, the cumulative risk for all conjunctions is plotted by altitude.

4 INITIAL LRC PLOTS

Fig. 4 is the initial LRC showing all conjunctions from July 1, 2020 to January 1, 2021. Some patterns are evident in this plot of 404,435 conjunctions (i.e., over 2,000 per day). The riskiest conjunctions occur between two DEBs (*i.e.*, FRAG and MD) but usually between two MDs, since they typically have higher masses (i.e., consequence).

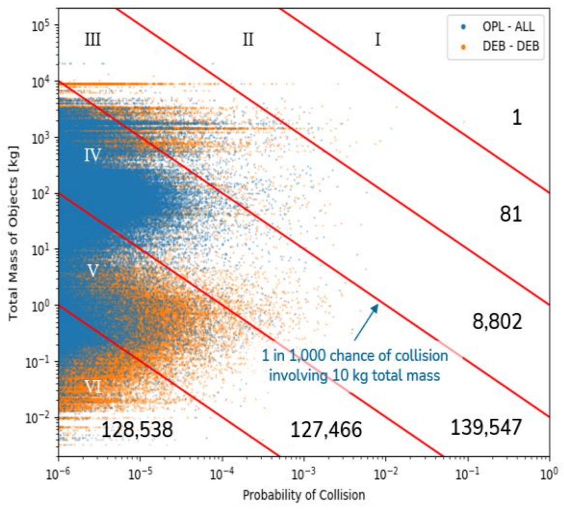

Figure 4. Nearly two-thirds of the ~404,000 conjunctions monitored were DEB-DEB, and only 2% (i.e., 8,884) of all conjunctions had a risk greater than 1E-2 kg.

The OPL-ALL encounter risk may be mitigated with space traffic management (STM) such as user-generated user ephemerides, collision avoidance (CA) maneuvers, and constellation maintenance. DEB- DEB conjunctions accounted for 64% of all conjunctions, while 2% had a risk greater than 1E-2 kg (*i.e.*, 0.01), which is equivalent to a near miss between objects with a combined mass of 10 kg and a PoC of 1E-3 (*i.e.*, 1/1,000 chance). The discrete horizontal lines are groups of similarly-sized R/Bs and PLs.

Fig. 5 shows the OPL-ALL and DEB-DEB populations separately with the number of events for each “risk region”. The highest risk region is region I (risk > 100 kg) and each contour marks a drop in risk by a factor of 100.

DEB-DEB conjunctions outnumber OPL-ALL events in all risk regions except for region IV. DEB-DEB conjunctions account for the majority of the low-risk events (*i.e.*, 77% from risk regions V and VI) due to the large number of low mass fragments as well as in the high-risk regions (*i.e.*, 77% from risk regions I to III), since the intact derelicts are generally more massive than OPLs in LEO.

Distinct population characteristics are evident in the plots. For example, the ellipse in the DEB-DEB plot shows conjunctions involving SL-16 R/Bs (8,900 kg each). The two highest risk DEB-DEB conjunctions are

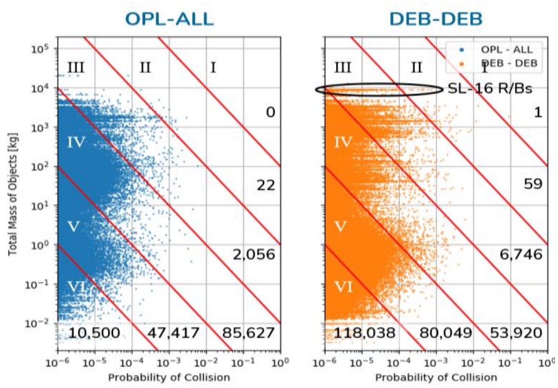

Figure 5. Both conjunction families have similar shapes, but the greater number of DEB-DEB at higher mass are due to clusters of R/Bs, while those at lower mass are due to the numerous fragments.

specific events involving two SL-16 R/Bs. Similarly, other distinct horizontal groupings in region III represent interactions between other R/Bs, such as SL-8s.

Risk by altitude is shown in Fig. 6. This plot amplifies the clusters of intact derelicts from the DEB-DEB conjunctions and accentuates the large number of moderate risk events between MDs at 1400-1500 km. This region has previously been identified as a region of concern due to minimal drag to remove this debris from orbit; the majority will linger for centuries. [16]

The large number of conjunctions below 850 km are typically low PoC OPL-ALL events, reflecting the rapid deployment of new satellite systems in the past two years. The vertical bands reflect popular orbits and constellations such as the International Space Station (ISS) and the Starlink constellation. The large mass of the ISS inflates the “risk”, as a fragment hitting the ISS would not destroy the structure. Similarly, the Starlink risk, as much of the OPL-ALL risk, may be mitigated by more accurate operator ephemerides, collision avoidance maneuvers, and constellation maintenance.

The “flat-bottomed” characteristics shown by horizontal arrows represent large numbers of similar-sized R/Bs and PLs at these altitudes. Additionally, the large DEB-DEB “cloud” at the low-risk end of the 600-1,200 km range shows the greater fragment population at those altitudes. Similarly, the large region of OPL-ALL events from 400-850 km is indicative of the large number of OPLs in that region.

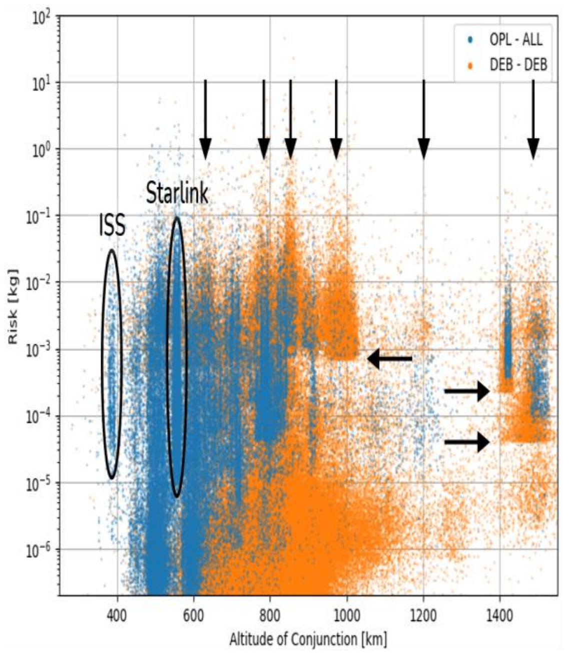

Figure 6. All conjunctions with a PoC greater than 1E-6, from LeoLabs data during the second half of 2020, plotted as a function of altitude of the encounter.

5 TOP 200 SMC CONJUNCTIONS

The 200 conjunctions with the greatest risk value (top 200 SMC) come from 367 objects (out of a maximum 400 possible objects). Of these 367 objects, 176 (48%) were of Russian/Soviet origin, with 90 (25%) being intact Russian derelicts (83 R/Bs and 7 PLs).

There were 92 (25%) of US origin and 70 (19%) originating from Chinese missions. Interestingly, while the Russians had roughly equal contributions from fragments, rocket bodies, and non-operational payloads, the US objects were primarily payloads and fragments, while the Chinese objects were mainly fragments and rocket bodies.

In previous MCMA calculations, fragments were not considered, but this analysis shows that fragments from three well-known breakup events are involved in 71 (22%) of the top 200 SMC conjunctions:

- Fengyun 1C: 39 objects
- Iridium 33/Cosmos 2251: 17 objects
- Cosmos 1275: 15 objects

”Repeat offenders” (i.e., objects that showed up more than once in the top 200 SMC events) include an SL-16 R/B (23705 / L1978) that was involved in five of the top 200 SMC conjunctions. Five objects were involved in three events: three more SL-16 R/Bs, a Russian PL (Cosmos 1674), and FLOCK 4P 12 PL.

The FLOCK 4P 12 PL was a surprise, as it is a 3U cubesat. On closer scrutiny, Cosmos 1674 and FLOCK 4P 12 had all three of each of their high-risk encounters with each other. This phenomenon is called coupling, when two unrelated objects have their orbits synchronized to have multiple close approaches. These two objects will be monitored carefully in the future.

Further, 36% of these top 200 SMC conjunctions were in the ~500-600 km altitude range; the remaining 64% occurred between ~725-1,000 km, with a peak around 830-850km. This peak coincides with the cluster of SL-16 RBs abandoned and referred to in previous work as Cluster 850 (C850).

The lower altitude peak of activity was suggested in previous analyses, [3, 12] due to the increased rate of deployments in that altitude range as well as the unintended consequence of compliance with the 25-year debris mitigation guideline.

The most frequent object type in the top 200 SMC conjunctions was Fengyun 1C debris, with 39 occurrences (20% of the conjunctions).

The intact object type that showed up the most was 35 SL-8 R/Bs (18%); there were even two occurrences when two SL-8 R/Bs were involved in a single top 200 SMC conjunction. SL-16 R/Bs (8,900 kg each) appeared 30 times (15%), highlighting the urgent need to remediate these massive derelicts.

For the top 200 SMC conjunctions, an operational satellite showed up 60 times. However, these encounters need to be considered differently from DEB-DEB conjunctions, since an operational satellite will often have better ephemerides than a derelict object as well as collision avoidance capabilities.

The number of encounters involving operational satellites highlights the frequency of satellite operators to consider potential encounters with debris. Four top 200 SMC occurrences involved two operational satellites (OPL-OPL).

While there are more debris fragments than massive derelicts, massive derelicts were three times more likely to pose SMC conjunctions with operational satellites. This is largely driven by the larger masses generating larger consequence. Note that the operational satellite's mission would be terminated either way - the "consequence" is merely the number of debris fragments likely to be generated.

Fig. 7 plots the risk data for the Top 50 SMC objects from previous analyses [12] within the LRC framework. While these 50 objects amount to only 0.3% of the LEO cataloged population, they were involved in 11% of all high-risk conjunctions (risk regions I, II, and III).

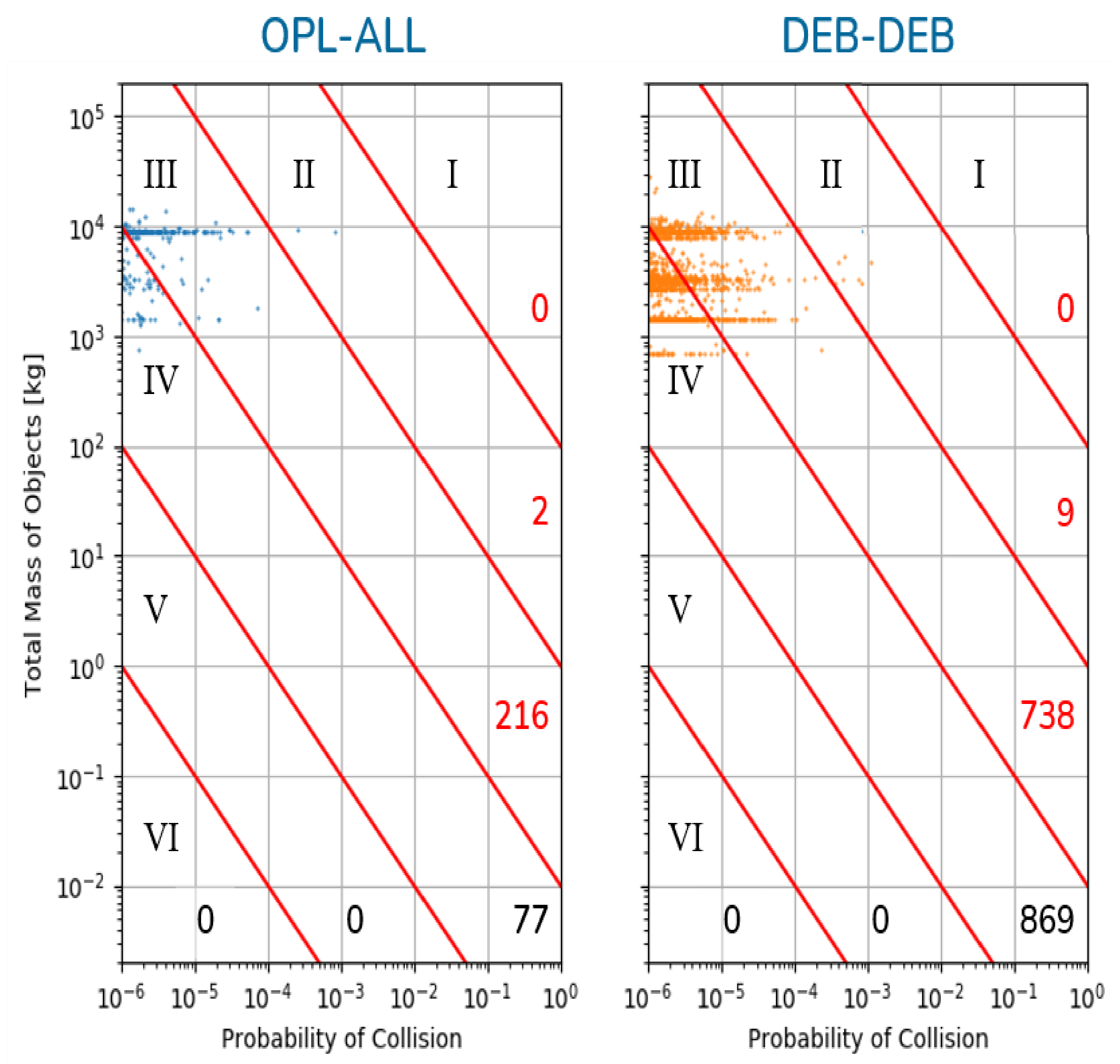

Figure 7. The Top 50 SMC objects [12] comprise 11% of the high-risk conjunctions (i.e., risk regions I, II, and III) from this study.

Fig. 8 shows the top 200 conjunctions as a function of altitude and latitude. The plot reinforces that the most debris-generating potential resides between 500 km and 1,000 km.

Similarly, it emphasizes that conjunctions more often occur at extreme latitudes rather than near the equator. For this data set, one third of the events occurred within ±51° latitude of the equator, the next third of the events spanned 21° (*i.e.*, within ±72°) while the remaining third occurred in only 11° (*i.e.*, between 72° and 83°.)

It is also evident that more OPL-ALL events occur below 650 km, while more DEB-DEB events occur between 750 km and 1,000 km.

The final depiction of LRC is the accumulated risk as a function of altitude, as shown in Fig. 9. The SMC aggregated risk by altitude shows that the larger number of lower risk events around 975 km accumulated to surpass the risk from the fewer but more consequential SL-16 R/B encounters near 840 km. In addition, the very large number of low-risk events between 1400 km and 1500 km almost grew to within 10x of the 840 km spike.

Below 600 km, the unmitigated OPL-DEB collision risk exceeds the DEB-DEB collision risk. This highlights the large number of small satellites operating in this region. Conversely, the fact that, above 600 km, the debris-generating potential from DEB-DEB exceeds the OPL-ALL risk accentuates the need for debris remediation.

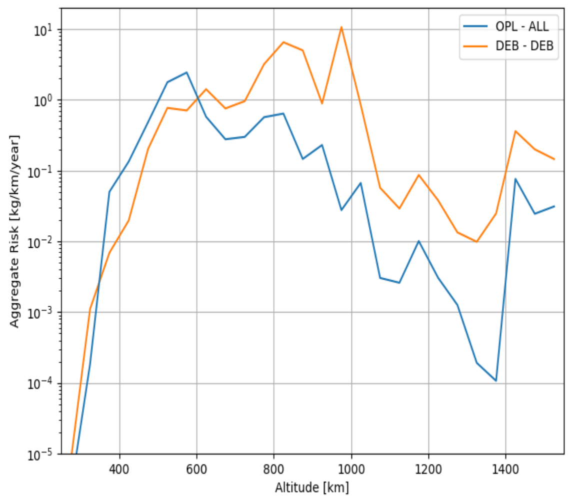

Figure 9. The aggregated risk by altitude exposes trends not obvious in the LRC; primarily, DEB-DEB risk is greater in LEO above 600 km.

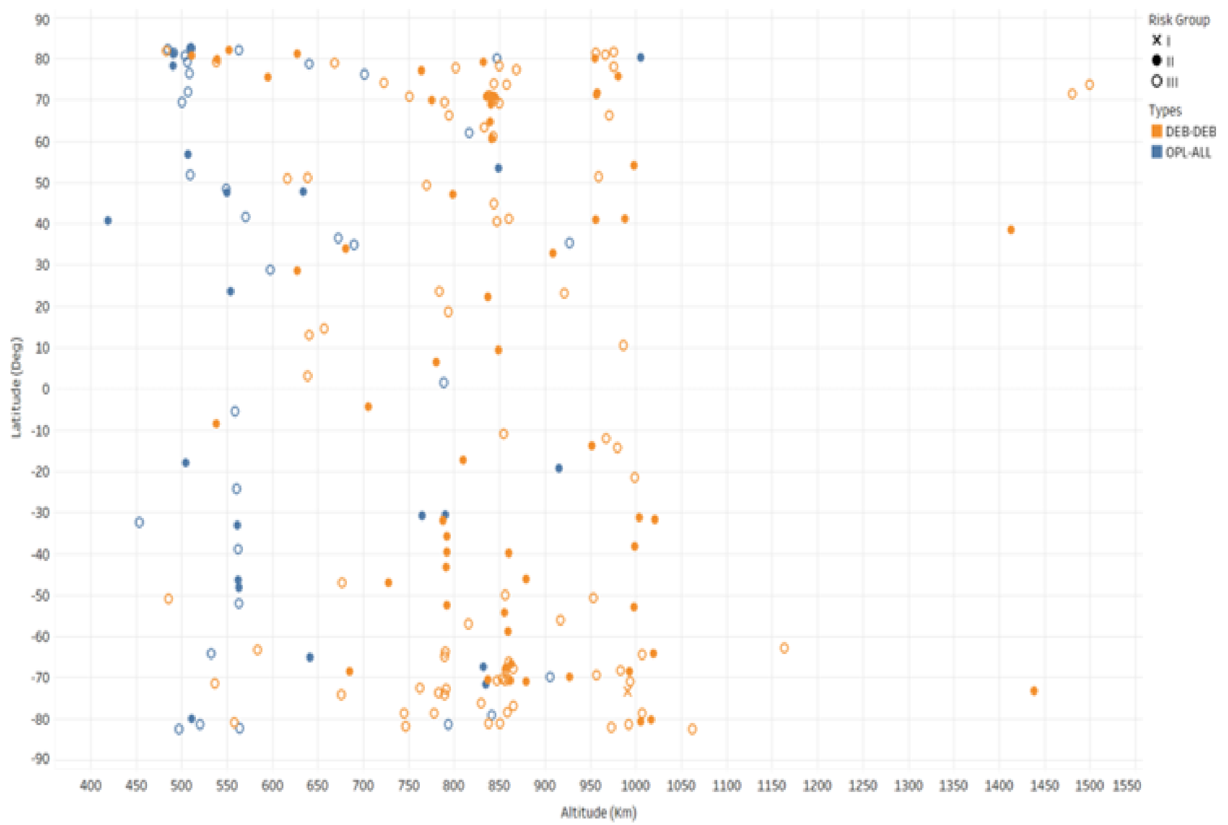

Figure 8. Conjunctions are more likely to occur at extreme latitudes and most debris-generating potential is between 500 km and 1,000 km.

6 CLOSING COMMENTS

The LRC has been created and will be maintained leveraging LeoLabs-derived data to provide a unique diagnostic tool for LEO objects and regions that have the highest debris generation potential.

Lessons from this analysis include the demonstration that trackable debris fragments interacting with massive derelicts present a measurable contribution to future debris-generating risk. Furthermore, the potential involvement of operational payloads in SMC conjunctions is worth exploring, though, as stated earlier, OPL-ALL events can potentially be mitigated with collision avoidance maneuvers, better operator ephemerides, and constellation maintenance.

Common themes between this analysis and previous research are that (1) hardware of Soviet/Russian origin pose a significant debris-generating potential in LEO, especially SL-16 and SL-8 R/Bs, and (2) peak risk for future debris generation is around 840-975 km but collision risk between 500 km and 600 km region is increasing, and (3) the altitude region between 1,400 km and 1,500 km has a significant DEB-DEB collision risk with a significant long-lived debris generation potential.

These graphs (and more) are built on the LeoLabs data platform that will be updated in real-time and will be interactive, allowing the user to perform specific risk calculations.

The analysis covered six months of data, which the authors feel is insufficient to demonstrate statistically-significant conclusions. The team plans to continue the processing of more data, and will provide updates and insights as the data set grows.

Several specific questions to be addressed in this continuing research activity include:

- How does the LRC evolve over time?
- What are the potential economic losses of operational satellites?
- What do we find by coupling statistical risk with conjunction dynamics?
- Does this analysis apply to orbit capacity thresholds?

The evidence from risk-based analyses points to several observations about collision risk in LEO: (1) SL-16 R/Bs are uniquely concerning to the future growth of debris; (2) the stochastic nature of conjunction dynamics makes it impossible to predict months in advance which specific collision will occur next, but the altitude regions where such a collision will likely occur is fairly clear; and (3) poor debris mitigation compliance, unclear STM principles, and the rapid increase of operational satellites contribute to the growing risk of significant debris-generating collisions in LEO.

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