PRELIMINARY ANALYSIS OF TWO YEARS OF THE MASSIVE COLLISION MONITORING ACTIVITY

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It is hypothesized that the interactions between many of the most massive derelicts in low Earth orbit (LEO) are obfuscated by being averaged across all of LEO. This is suggested by the fact that there are clusters of derelicts where members' inclinations are nearly identical and their apogees/perigees overlap significantly resulting in periodic synchronization of the objects' orbits. In order to address this proposition, an experiment was designed and conducted over the last two years. Results from this monitoring and characterization experiment are presented with implications for proposed debris remediation strategies. Four separate clusters of massive derelicts were examined that are centered around 775km, 850km, 975km, and 1500km, respectively. In aggregate, the constituents of these clusters contain around 500 objects and about 800,000kg of mass; this equates to about a third of all derelict mass in LEO. Preliminary analysis indicates that encounter rates over this time period for these objects are greater than is estimated by traditional techniques. Hypothesized dependencies between latitude of encounter, relative velocity, frequency of encounters, inclination, and differential semi-major axis were established and verified. This experiment also identified specific repeatable cluster dynamics that may reduce the cost/risk and enhance the effectiveness of debris remediation activities and also enable new operational debris remediation options.

INTRODUCTION

The aerospace community has rightfully spent significant resources considering how to prevent the potential for the cascading of the debris environment (i.e., the Kessler Syndrome) that was identified decades ago. [1] The typical response to combatting the Kessler Syndrome is the steady, long-term removal of abandoned rocket bodies and payloads (i.e., five objects a year for 100yrs). [2] The typical active debris removal (ADR) analysis assumes that we are unable to determine which events might occur first so the overall effect is that one must remove 35-50 objects on average to prevent a single collision and around 15 collisions are anticipated to occur in this scenario (which would erode space flight safety significantly even while preventing environmental instability).

The hypothesis of the research presented in this paper is that current space flight safety is a more relevant objective than long-term environment stability.

More pointedly, if short-term space flight safety is assured by preventing the most significant collision events then environment stability will in turn be assured; the reverse is not true.
Assurance of immediate space flight safety as the primary objective has encouraged us to examine the possible short-term, highly consequential events (rather than trying to determine the average collision hazard across the entire cataloged population). This refocus led us to examine debris "hot spots" in Earth orbit where the most massive objects might interact with each other at hypervelocity speeds (i.e., above 6km/s) and at frequencies greater than estimated by the current model (i.e., typical combination of the kinetic theory of gases analogy incorporated with the Poisson probability distribution function). [3]

It was shown previously that two SL-16 rocket bodies colliding around 850km would result in the reduction of the operational lifetime of all satellites in the 650-1050km altitude range by an average of 10%. [4] An examination of the satellites residing within this altitude range amount to at least \$10-15B [5] of operational space systems; 10% of this asset pool is indeed significant.

A focus on individual events within specific clusters of massive derelicts has produced empirical data documenting the number and proximity of conjunctions between these massive objects. In the spirit of establishing a culture of safety, it is imperative to monitor, characterize, and share information about these individual events in order to motivate responsible action.

A recent review of aerospace and business catastrophes clearly show the importance of such communications: *"Multiple near misses preceded (and foreshadowed) every disaster and business crisis we studied and most of the misses were ignored or misread."* Our work also shows that cognitive biases conspire to blind managers to near misses. Relevant cognitive biases are normalization of deviance (i.e., over time accept anomalies) and outcome bias (i.e., focus on results more than, often unseen, complex processes)." [6] As a matter of fact, the experts in the psychology of anomaly reporting and risk acceptance state that "viable approaches to preventing [such] catastrophes is to observe near-misses and use them to identify and eliminate problems before they produce large failures." [7]

This paper investigates the "hot spots" as per a culture of safety by asking different questions: what are the most consequential events that can occur in low Earth orbit (LEO); what does the average collision event within the satellite catalog really mean; can we predict the most likely next massively catastrophic collision; can we enhance the utility of ADR operations; can we respond to an individual potential collision; etc. The higher orbital velocities, higher mutual inclinations, and a higher concentration of debris all in LEO made it so that all of the most risky clusters were in LEO.

Just like Henry Ford said: "If I had asked my current customers what they wanted they would have a said a faster horse that ate less." The authors of this paper are trying to ask new questions with a different objective in mind (assure immediate space flight safety more than assuring long-term environmental stability). Most importantly, we have strived to create a long-term experiment where we iteratively hypothesize potential cause and effect theories with new rounds of data capture and analysis. [8]

In summary, we are striving to break out of the cognitive bias to <u>study</u> (100yr evolution models), <u>wait</u> (for someone to develop ADR solutions), and <u>hope</u> (that massive collisions will not occur) by following a sequence of <u>monitor</u> (examine interactions amongst clusters of massive objects), <u>characterize</u> (determine cluster dynamics relevant to debris remediation prioritization) to provide a basis for responsible <u>action</u> (e.g., remove the "worst offenders" or create an emergency response capability to prevent imminent collisions).

This experiment is called the Massive Collision Monitoring Activity (MCMA).

<u>MCMA BASICS</u>

The clusters identified for the initial MCMA effort were selected considering (1) proximity of apogees and perigees (i.e., clumped in altitude); (2) common inclination values (speculated to cause greater interaction rates); (3) total mass involved in a potential collision; and (4) altitude of the center of the cluster (i.e., high enough so that debris produced would be long-lived).

These criteria resulted in the selection of four clusters in LEO that include nearly 500 objects that have an aggregate mass of nearly 800,000kg. The table below provides the salient characteristics of the four clusters. The clusters are named by their centering altitude; C975 centered at roughly 975km altitude.

Table 1. The four clusters that MCMA have been monitoring are the "hot spots" in LEO as the collisions will be the most consequential and the probability of collision may be greater than modeled.

Cluster Name	Cluster Member	Mass (kg)	Number	Apogee (km)	Perigee (km)	Inclination (deg)
C775	SL8 RB	1,434	44	793	733	74
	SL8 PL	850	44	802	742	74
C850	SL16 RB	8,300	18	860	814	71
	SL16 PL	3,250	18	868	823	71
C975	SL8 RB	1,434	144	1020	935	83
	SL8 PL	800	142	1024	934	83
	Other PL	1500	15	997	905	64
C1500	SL8 RB	1,434	17	1660	1330	74
	SL14 RB	1,407	24	1530	1363	83
	SL14 PL	2477	24	1507	1381	83
TOTAL		**~756k**	**490**			

Overall, the four clusters have distinctly different characteristics in mass span (total mass of derelicts divided by altitude in which their orbits reside, kg/km), number span (total number of objects divided by the altitude in which their orbits reside, #/km), and annual collision rate (CR/yr) as shown below, respectively:

	Mass Span	Number Span	CR/yr
C775:	1393kg/km,	1.39#/kg,	1/413
C850:	**3850kg/km**,	0.67#/km,	1/578
C975:	2610kg/km,	**2.55#/km,**	**1/92**
C1500:	539kg/km,	0.32/km,	1/1345

The maximum value in each category is bolded above emphasizing that a collision in C850 will be the most catastrophic, but a collision is most likely to occur in C975.

Encounter Statistics

The number of encounters within a given distance (e.g., 5km and 1km) provides a measure of the interaction amongst cluster members. These numbers can be used to compare how much each cluster is interacting relative to what would be predicted using the combination of the kinetic theory of gases (KTG) and Poisson probability density function. Appendix B provides a full development of the combined KTG/Poisson model.

The table below depicts the monthly encounter rates while Appendix C contains a monthly accounting of interactions for each cluster and statistics on the total set of encounter data summarized in the table below.

As would be expected from examining the data above, C975 has the greatest number of encounters as it has the greatest concentration of objects (2.55 objects/km) which yields the greatest predicted collision rate between the members of the cluster (1/92 per year).

Table 2. The encounter rates for 1km and 5km miss thresholds do not directly provide an absolute measure of collision risk but they do provide a means to compare measured data against the standard KTG/Poisson combination assumed to be accurate for modeling orbital debris interactions.

	C775	SL-16 R/Bs	C850	C975	C1500
#<5km/mon	197	18	65	1818	36
#<1km/mon	11	1	2	75	2
#<5km/#<1km	18	18	**33**	24	18

These encounter rates have been found to be between three to six times greater than what would be predicted using the standard KTG/Poisson modeling combination.

There have been over 21,000 conjunctions less than 5km recorded in the last two years for all of these clusters with the vast majority occurring in C975 over the last year. Additionally, there have been nearly 200 encounters within 500m over the last two years of the MCMA effort.

As of 1 July 2017, there have been 246 events (14 in C775, 7 in C850, 223 in C975, and 2 in C1500) that if either object were an operational satellite it would have triggered the issuance of a Conjunction Data Message (CDM) by the Joint Space Operations Center (JSpOC) (i.e., total miss <1km and radial miss <200m).

The ratio of <5km passes to <1km passes is an important parameter that has been speculated by Dan Oltrogge that it should asymptotically approach 25 (i.e., 5^2). [9] As can be seen in Table 2, two of the clusters and the SL-16 rocket bodies (i.e., half of C850) approach 18 for this ratio and C975 is 24 but C850 is significantly higher at 33. However, by examining data from all of the clusters and several combinations of miss distances (such as 4km vs 2m or 3km vs 1km) much higher correlations are found with the proposed relationship.

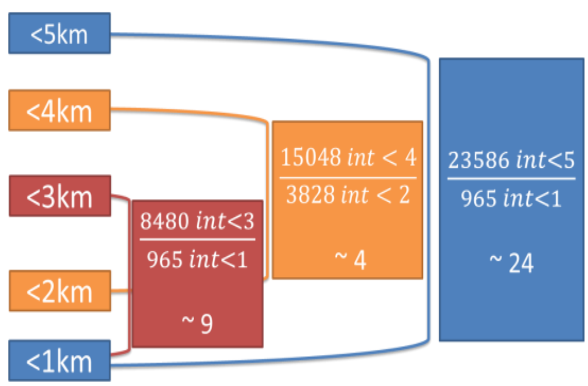


Figure 1. The ratio expected between conjunctions of different thresholds follow the relationship proposed by Dan Oltrogge. For example, the number of conjunctions within 3km is nine times more than 1km misses.

For C975, there have also been ten near misses less than 100m in the last year and for C850 there have been six near misses less than 500m in the last year. As stated earlier, the very large number of 5km misses really do not contribute to any real collision risk but rather just provides a means to compare model applicability to these clusters versus randomly distributed debris. However, when the misses start to get less than a few hundred meters, this is no longer true, especially considering that most interactions have a relative velocity of ~14km/s..

It is hoped that this analysis and reporting of near misses will motivate the community to start debris remediation (ADR and just-in-time collision avoidance, JCA) soon. JCA is a remediation option whereby imminent collisions are prevented by nudging one of the two objects out of the path of the other object. This remediation approach may indeed provide a cost-effective and responsive complement to ADR. [3,4]

Worst Offenders

A major portion of the MCMA effort is to determine the efficacy of selecting the "worst offenders" (i.e., identify primary objects for ADR) before they are on a collision course with another massive derelict. First, each cluster is evaluated generally to identify the worst "hot spot" in LEO. C975 has a slightly higher immediate risk (~43 to ~28 for C850) but it also will have a greater persistence as debris produced in C975 will have ~3x longer orbital lifetime than debris from a C850 event. While C1500 has the lowest immediate risk, debris liberated in C1500 will persist ~10x versus C975.

Table 3. Cluster ratings show that C975 and C850 are the highest immediate risk clusters.

	Probability (CR/yr)	Consequence (Trackable Debris Created)	**"Risk" (Probability x Consequence)**	Persistence (lifetime, yrs, for $0.01m^2/kg$)
C775	1/413	3,500	**~9**	300
C850	1/578	16,000	**~28**	500
C975	1/92	4,000	**~43**	1,800
C1500	1/1345	6,000	**~5**	20,000

For individual objects, the scoring is done by (1) frequency of interactions (34%), (2) potential consequence of collision (33%), and (3) potential probability (33%, combination of low eccentricity and overlap with largest number of fellow cluster members). The table below summarizes the analysis performed to determine which ten objects in these clusters would individually be considered the worst offenders and, thus, warrant removal first.

It should be noted that the makeup of the two clusters must also be considered when determining which objects might be suggested for removal first. Clearly, C850 and C975 pose the most significant risk for potentially massive amounts of debris generation in the future. However, while it is relevant to select the individual objects that are the "worst offenders" (i.e., contribute the most to this debris-generating risk) a final selection of any object cannot be done exclusive of the overall impact its removal might have on the cluster dynamics.

Table 4. The worst of the worst offenders are all rocket bodies from C975 (SL-8) and C850 (SL-16).

Satellite Number	Cluster
15056	C975
32053	C975
22220	C850
22566	C850
22285	C850
23088	C850
23405	C850
31793	C850
25407	C850
28353	C850

For example, if all individual risk characteristics are equal between C850 and C975 objects, we may lean toward the removal of C850 objects since eliminating ten objects from C850 (only has 36 objects) will likely create a much greater incremental change in risk than ten objects from C975 (has 301 objects).

Specifically, it was determined that removing the ten "worst" objects out of C975 would produce ~10% fewer interactions (less than 5km) while the ten worst being removed from C850 would result in a ~60% reduction of close approaches. In addition, the amount of mass removed would be ~14,000kg for the C975 removals (4% of the mass within C850) but ~83,000kg or a reduction of ~60% of the C850 aggregate mass is the result of removing 10 SL-16 rocket bodies.

From a detailed examination of the intermediate results, it is clear that C850 objects have been singled out for the combination of high mass (i.e., higher potential consequence) but also the lower eccentricity values which results in more close approaches which leads to greater potential probability of encounter and orbit synchronization.

Probability of First Event

While the Poisson probability distribution has been used often to determine probability of collision and collision rate for orbital debris applications, there is also a less well-used statistic: the gamma distribution that predicts the probability of the timing for the first event to occur.

The total development of the KTG/Poisson combination to include the Gamma distribution and Gamma values for all of the clusters is provided in Appendix B. The primary observation from this analysis is:

For C975, within which a collision would produce ~4,000 cataloged fragments, there is a ~11% chance that statistically such a collision could have already occurred.

Similarly, for C850, within which a collision would generate ~16,000 trackable fragments, there is a ~1% chance that statistically such a collision could have already occurred.

Predicting Conjunctions

As part of the MCMA, it has been verified that we are capable of predicting the conjunction of these massive derelicts to within 5-14% of the miss distance five days before the encounter as shown in the figure below. The term eGP in the legend denotes the use of the enhanced General Perturbation two-line element (TLE) sets from Space-track.org for these analyses. It should be noted that element sets derived general perturbations will be less accurate than those derived with special perturbations propagators.

This capability to predict close encounters many days in advance may provide a mechanism to improve the return on investment from ADR operations by possibly making an ADR mission serve as an emergency response (e.g., just-in-time ADR or JDR) rather than strategic cleanup process over decades. In addition, the ability to predict the close approaches accurately five days in advance may enable the use of

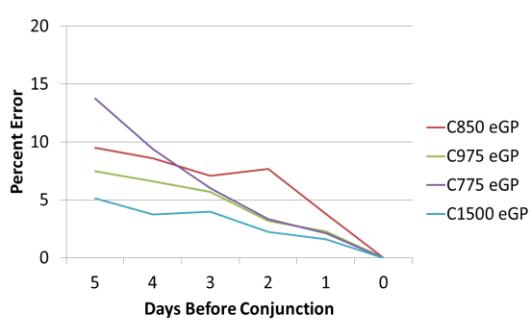


Figure 2. The accuracy of predicting conjunctions improves as we increase in altitude and as we get closer to the conjunction date/time.

JCA to prevent collisions. Previous analyses have shown that existing sounding rocket technology is responsive enough to operate under these timelines, however, there are still some challenges related to the accurate placement of a nudging cloud. [3]

Analytical Modeling of Cluster Behavior

While collecting experimental data for these clusters provides ground truth, it is instructive to compare this empirical data with theoretical calculations. Taking the apogee, perigee, and inclination for each member of the clusters of greatest importance (i.e., C850 and C975) and computing collision geometry under the assumption of randomized right ascension of ascending node, argument of perigee, and mean anomaly, it is possible to compute the time-averaged collision rate between any two members of the cluster.

This is typically how collision rates are computed, and taking into account the full geometry of the satellites – especially inclination – it is also possible to compute expected collision rate distributions in direction and relative velocity. However, these calculations integrate the risk over all geometries, and therefore represent integration over a very long span of time. They do not give us information on how individual objects can have multiple repeated close approaches, only how those multiple encounters would average out in the long term.

We can take the empirical results and compare to these predictions and compare results. The figures that follow show both the encounter rate and relative velocity distributions for C850 and C975 for the last year.

As can be seen in Figures 3 and 4, sometimes multiple repeating encounters can make the empirical counts diverge from the theoretical ones. To account for this, sampling error uncertainties are computed using a Bootstrap method. This statistical tool resamples from the data, with replacement, to scale how sensitive the data is to the presence of each individual satellite.

In the upper panel of Figure 3, we plot the number of encounters with a given encounter radius and less. As we increase the encounter radius, the number of cumulative encounters grows as approximately the square of the radius, corresponding to the encounter area. The empirical data is in red, and the theoretical calculations in black. Note that the empirical data exceeds the theoretical for encounter radii larger than about 1 km. However, when the empirical number is corrected for sampling error, the +/- 1-sigma uncertainty bands bracket the theoretical curve. The rather large uncertainties are being driven by a single pair of satellites with a large number of repeating conjunctions. Note that we would expect approximately one encounter as close as 200 meters, but the closest recorded value was 260 meters.

In the lower panel of Figure 3, we bin the actual encounters in measured delta-velocity to the theoretical values for C850. We see overall a good fit to the theoretical predictions. However, there is a "spike" in encounters in the 3.0 - 3.5 km/sec bin. This is due to the pair of satellites that had multiple encounters (i.e., an extended walk-in sequence).

However, when we include the sampling error 1-sigma bounds, the theoretical curve is still bracketed by the (very large) uncertainty. If we could observe for a longer time or had more data points, these uncertainty bounds would likely shrink.

As a matter of fact, C975 has a much greater number of encounters so the statistics are improved. The upper panel of Figure 4 shows the encounter rate comparison for C975 and the overall theoretical curve matches the empirical data quite closely. The closest predicted encounter is around 30 meters, while the closest recorded encounter was 27 meters.

The lower panel of Figure 4 depicts the delta-velocity binning for C975. In this case, the predicted number of high-velocity encounters is higher than the empirical values. The differences are small, but probably due to simplifying assumptions on the calculations.

From Figures 3 and 4, that have plotted MCMA results against a theoretical simulation, it is clear that the overall statistics match the predicted calculations quite well. C850 has a smaller number of encounters than for C975, so the uncertainties are larger. Even so, the data typically falls within the 1-sigma sampling error bounds.

The simulated encounter rate distributions suggest the closest encounter for C850 to be about 200m and it was actually close; 260m. Similarly, the C975 simulation suggests the closest approach over a year's time to be about 30 meters and in reality it was 27m with five more in the 60-70m range. At these small miss distances we anticipate reasonable errors are possible in the measured miss distances due to random variations.

We should point out that the repeating encounter for C850 consisted of 97 separate close approaches (within 5 km) between objects 19650 and 25407 over several days in September, 2016. This unusually long-lasting encounter was undoubtedly due to the two objects having almost identical orbital periods. Statistically, for every such pair with multiple repeating encounters, there may be many pairs of objects, also with nearly identical periods, that assiduously avoid encountering each other, such that the long-term average should approach the theoretical values. This phenomenon is not captured in the theoretical calculations directly, and is only implicitly included in the calculations.

It is precisely this behavior that may allow satellite operators to identify potentially troublesome objects in their orbital vicinity, and by avoiding them by maneuvering, may have a disproportionate effect on the overall risk.

In summary, the analytic simulation shows clearly that these subsets of the LEO debris environment that could potentially create significant debris-generating events do have high encounter rates and high relative velocities. This partitioning of the debris population is replicated accurately via analytic simulation and points toward the benefit of examining smaller but relevant subsets of the debris population to help identify debris "hot spots" in Earth orbit.

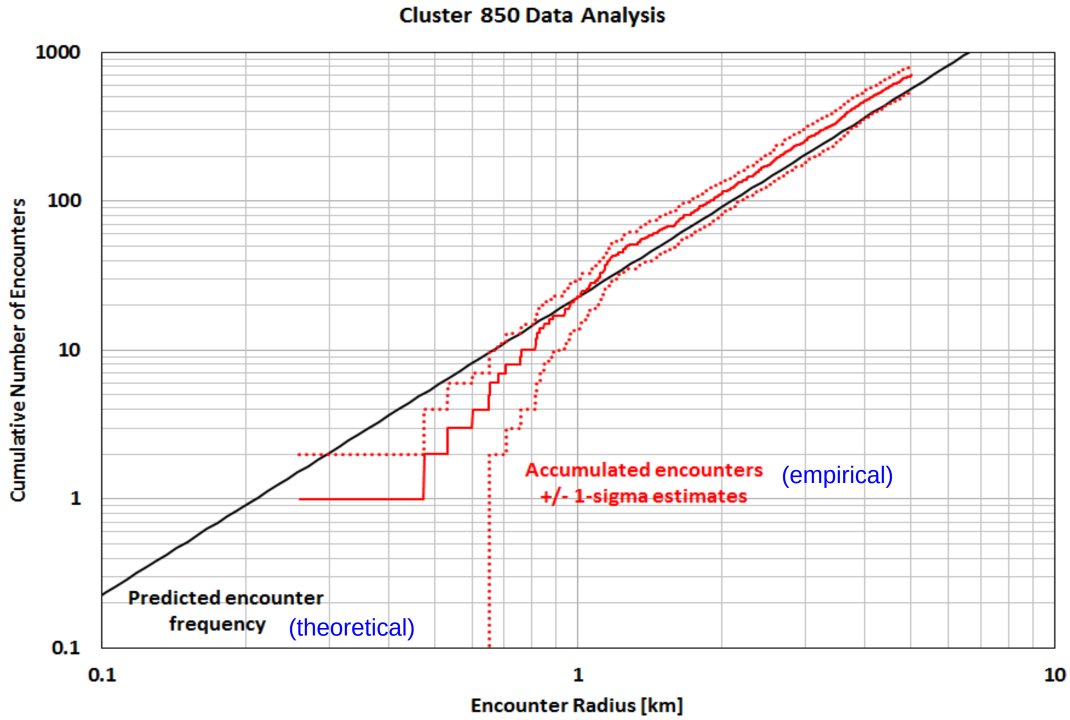
EXPANDED MCMA

The motivation for MCMA was to monitor and characterize a small, but consequential, subset of the cataloged population with the hypothesis that they pose the majority of the risk for large debris-generating events. Indeed, it is without debate that encounters within the four clusters monitored within MCMA produce the vast majority of the most consequential collision events in Earth orbit.

It has also been shown that the members of the clusters (especially C850) do appear to be interacting at greater frequencies than is model by the KTG/Poisson combination. However, while these four clusters account for ~500 massive derelicts amounting to ~800,000kg of mass (i.e., 1/3 of derelict mass in LEO), there are still hundreds of massive derelicts that are not in "clusters" and, thus, are not accounted for.

It would be prudent to consider more objects in order to try to be more complete in the assessment of the massive derelict population. Over 300 more objects amounting to an additional ~700,000kg of additional mass have been added to the first four clusters.

number of encounters with a given encounter radius and less. As we increase the encounter radius, the number of cumulative encounters grows as approximately the square of the radius, corresponding to the encounter area.



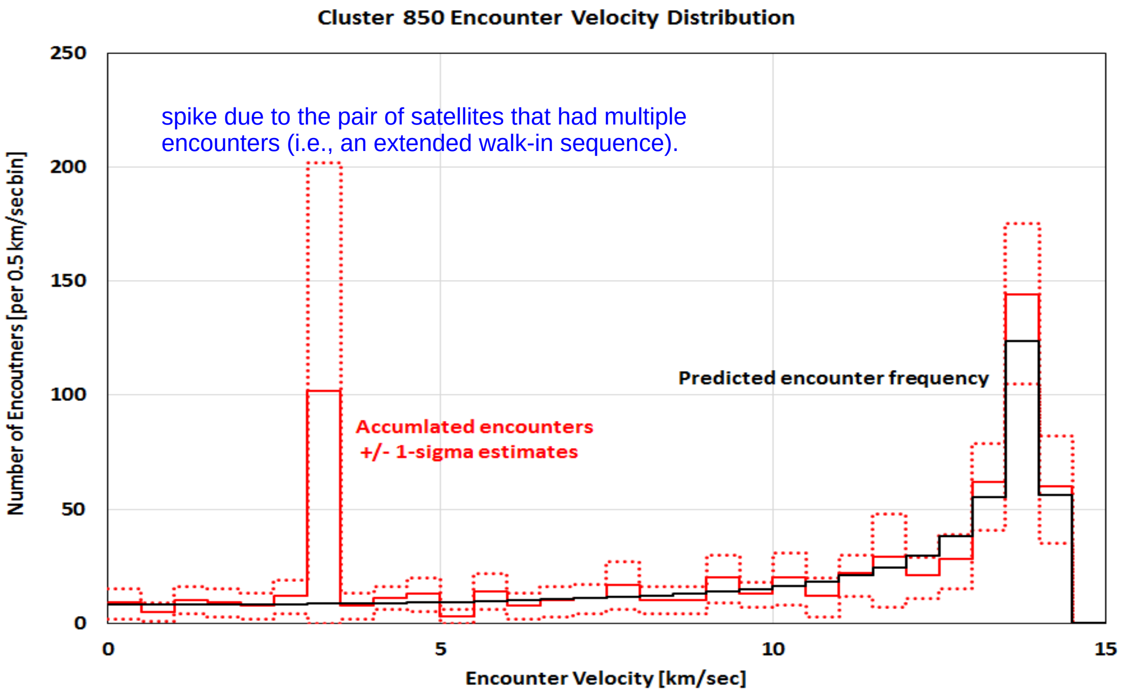
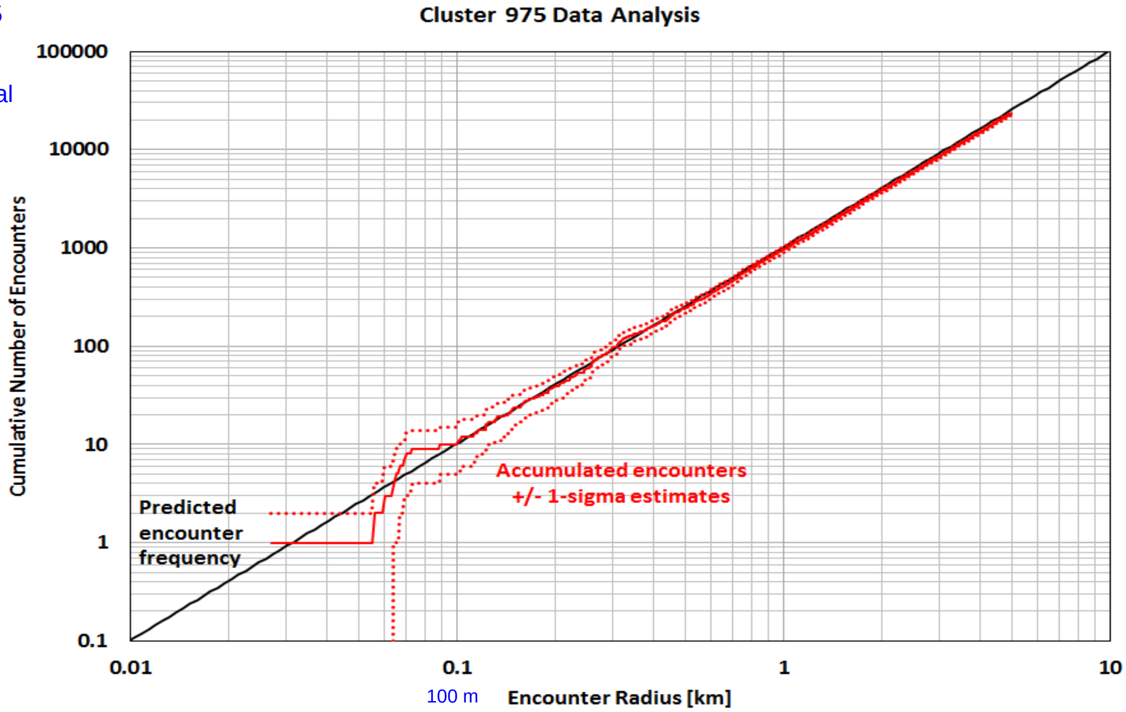


Figure 3. The simulated data for C850's encounter rates and relative velocities for the near misses less than 5km are plotted above. The upper panel contains the miss distances while the lower panel shows the relative velocity values. There is good comparison between the experimental data and the simulation even though there were only 36 objects involved in less than 1000 encounters. One significant walk-in skewed the relative velocity curve.

encounter rate comparison for C975 and the overall theoretical curve matches the empirical data quite closely



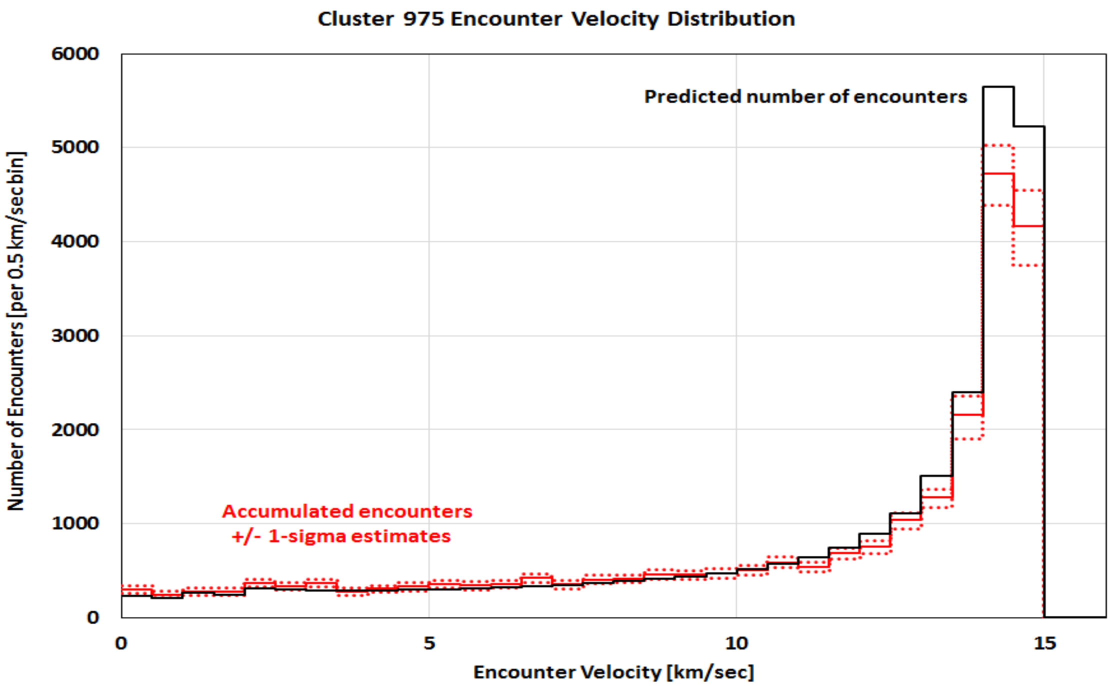


Figure 4. The simulated data for C975's encounter rates and relative velocities for the near misses less than 5km are plotted above. The upper panel contains the miss distances while the lower panel shows the relative velocity values. There is excellent comparison between the experimental data as would be expected as there are over 300 objects involved in more than 20,000 encounters in a year. However, the relative velocity distribution has a slight overprediction of the high velocity encounters (14-15km/s).

The threshold for inclusion has two parts: (1) crosses the 700-2000km altitude range (i.e., LEO) and (2) has a mass greater than 2,000kg. The total is now nearly 800 objects amounting to about 1.6 million kilograms of mass (i.e., about 2/3 of derelict mass in LEO).

The figure below depicts the state of the massive objects being considered by MCMA in the initial "compelling" version and the new "complete" framework. The original four clusters are the dark rectangles in the figure. Each of the four clusters had derelicts within their altitude range (but previously excluded since they did not have the inclination value(s) for each cluster); these were added to each cluster (i.e., "new" C850, etc).

A new C1200 was also created to cover massive objects that fall between C975 and C1500. Appendix A identifies the general makeup of the new clusters. Cleo includes all objects that stay within the 700-2000km but spans more than one of the clusters. Finally, Chigh contains massive objects that reside in highly elliptical orbits nominally being rocket bodies abandoned in geosynchronous (GEO) transfer orbits (GTO) or medium Earth (MEO) transfer orbits (MTO). Chigh contains nearly 200 objects amounting to over 570,000kg (roughly 75% of the total mass originally contained within the four "pure" clusters). Chigh is a unique population subset since if one of these objects were to fragment, the debris cloud would transit between LEO and GEO/MEO creating a potential cross-contamination hazard.

The new clusters analyzed for a complete characterization of debris-generating collisions are now C775N, C850N, C975N, C1200N, and C1500N where each one considers interactions amongst themselves and with Cleo and Chigh. It is our hypothesis that there will be few "new" encounters in the new clusters as compared to the four original clusters. However, it is imperative that this process be completed, and over the next year, the characterization of these new clusters will help to answer the question as to whether they warrant daily scrutiny. In 60 days of monitoring (1 May 2017 to 31 July 2017), these new objects, that contributed a ~60% increase in number of objects monitored, resulted in only a 25% increase in the number of conjunctions. More pointedly, the ~40% number increase due to Chigh only yielded ~1% more conjunctions. This result is what was anticipated but this larger screening population reduces the chance that some highly consequential, low probability conjunction will be missed.

The five new clusters now contain about 60% of the derelict mass that resides in or crosses LEO in its ~800 objects. Expanding the objects to be monitored by MCMA not only expanded the mass (~1.5M kg out of ~2.5M kg in LEO) and number of objects

Figure 5. The new set of objects to be monitored and characterized by MCMA provides a more complete coverage of massive derelict encounter possibilities: ~800 objects amounting to ~1,600,000kg.

under examination but also now contains derelicts from all major spacefaring countries. Over the next year, the research team will provide updates on the entire population being monitored.

In addition to considering a more complete population for monitoring, the research team is also implementing enhanced characterization features to include severity of event (i.e., estimate number of trackable fragments and LNT), deterministic probability of collision for events with miss distances smaller than a few hundred meters, and refining the worst offenders analysis.

SUMMARY/CONCLUSIONS

This preliminary examination of the years of monitoring four clusters of massive derelicts in LEO have resulted in several clear findings:

- Objects in similar orbits interact more frequently than modeled by tools that assume a random interaction process. This higher interaction rate is largely manifested in the walk-ins between cluster members driving encounter dynamics.
- Within these LEO clusters, 80-90% of the interactions exceed hypervelocity speeds (i.e., greater than 6km/s). The typical observation that encounter speeds in LEO are 10km/s is somewhat misleading since for these clusters the medians are around 12km/s and modes are close to 14km/s.
- The worst offenders (i.e., proposed first objects for removal by ADR operations) have been determined using a preliminary set of metrics that highlighted the importance of the massive rocket bodies in C850 but also two particularly troubling rocket bodies in C975. More research is planned to determine how much emphasis should be placed on the observed frequency of close interactions; is it an indicator of a worst offender or a counter-indicator?
- The "pure" clusters have provided an efficient means to assess the bulk of the possible catastrophic debris-generating events, however, it is also important to consider a wider range of massive objects to insure a more complete risk assessment process. Preliminary examination of the new additions to the MCMA seem to support the fact that the original four clusters provide an efficient assessment of the worst possible collisions that might occur in space but more research is required to assess this hypothesis more accurately.

REFERENCES

1. Kessler, D. "Collision Frequency of Artificial Satellites: The Creation of a Debris Belt", Journal of Geophysical Research, Vol. 83, No. A6, 1978.
2. Liou, J.-C., Johnson, N.L. A sensitivity study of the effectiveness of active debris removal in LEO. Acta Astronautica 64, 236–243, 2009a.
3. McKnight, D., "Proposed Series of Orbital Debris Remediation Activities", 7th European Conference on Space Debris, Darmstadt, April 2017.
4. McKnight, D., Di Pentino, F., and Knowles, S., "Massive Collisions In LEO - A Catalyst To Initiate ADR," 65th International Astronautical Congress, Toronto, CA, September 2014.
5. Approximate cost of existing satellite systems was determined by examining databases at http://www.satview.org and http://uscusa.org.
6. Robin Dillon Merrill: Tinsley, C., Dillon, R., and Madsen, P., "How to avoid catastrophe," HBR, April 2011.
7. Dillon, R.; Tinsley, C.; Madsen, P.; and Rogers, E.; "Organizational Correctives for Improving Recognition of Near-Miss Events" Journal of Management, Vol.42, No.3, March 2016 671-697.
8. Super Crunchers by Ian Ayres, Bantam Books, New York, NY. 2007
9. Oltrogge, D. and Alfano S., Collision Risk in Low Earth Orbit, 67th International Astronautical Congress (IAC), Guadalajara, Mexico, 26-30 September 2016.

APPENDIX A: Cluster Descriptions

ORIGINAL CLUSTERS	#	Range of i	Max (km)	Min (km)	Total Mass (kg)
C775	88	0.08	802	733	96096
C850	36	0.23	868	814	207900
C975	301	18.3	1024	891	333823
C1500	65	8.64	1677	1335	118242
Total	490	---	---	---	756061
ADDITIONAL OBJECTS					
C775N	13	63.73	814	669	51270
C850N	39	32.03	908	806	74252
C975N	13	34.27	1013	881	35940
C1200N	8	36.99	1276	904	16385
C1500N	4	33.52	2013	1288	14655
Cleo	22	35.73	2056	504	61359
Chigh	192	98.39	69991	112	571134
Total	291	---	---		824995
TOTAL OBJECTS					
C775N	101	63.73	814	669	147366
C850N	75	32.03	908	806	282152
C975N	314	34.71	1024	881	369763
C1200N	8	36.99	1276	904	16385
C1500N	69	33.52	2013	1288	132897
Cleo	22	35.73	2056	504	61359
Chigh	192	98.39	69991	112	571134
Total	781				1581056

APPENDIX B: Kinetic Theory of Gases and Poisson Probability Distribution Function Development

ʎ is the frequency within the Poisson probability density function (i.e., P(k)) taken from the kinetic theory of gases analogy.

$$\lambda = AC * VR * SPD \qquad (1)$$

where $SPD = \frac{N}{Vol}$ *= spatial density, #/km*^{3}
N = number of derelicts,
Vol = volume swept out by cluster, km^3
AC = collision cross section, km^2
VR = relative velocity, km/s

$$P(k) = \frac{\lambda^k e^{-\lambda}}{k!} \qquad (2)$$

where *λ = expected # of occurrences over time, t*
k = number of occurrences (k = 0,1...)

When it is assumed that there will be very few events, the probability of that rare event can be determined by 1 (i.e., the total all possible occurrences) minus the probability of no events. The result is represented by the well-known expression in equation (3).

$$P(1) = 1 - e^{-\lambda t} \qquad (3)$$

The PC is the collision hazard to one satellite from N objects in the population. PC is only concerned with the target, e.g., operational satellite getting hit by cataloged debris. Conversely, for a cluster of derelicts we are concerned about collisions between any two of the N objects in the cluster. This is called the collision rate (CR) and is the cumulative PC for N objects on each other. CR is represented by:

$$CR = \sum_1^N PC = \left(\frac{1}{2}\right) N\,(AC * VR * SPD * T) \qquad (4)^{[1]}$$
$$= (N^2/2) * (AC * VR * T) / (Vol)$$

When the encounter dimension is considered to be half of the miss distance then the collision rate is equivalent to the encounter rate (ER). The next logical question is "if we accept the probability found with a Poisson distribution, when might the first collision occur?" Using a gamma distribution, this can be evaluated for a given confidence level in equation (5).

$$\Gamma = -\ln(1 - C) * \left(\frac{1}{CR}\right) \qquad (5)$$

where *Γ = # of years until the first event*
C = confidence interval
CR is Poisson-derived encounter rate

The table below provides the Gamma table for the four original clusters. The 100% column is the date when the cluster was fully populated (i.e., the clock started ticking) and CR is the annual collision rate for that cluster.

	100%	CR	% First Event
C775	1994	1/500	4%
SL-16	2007	1/3000	0.3%
C850	2007	1/1000	0.8%
C975	2007	1/100	**11%**
C1500	2001	1/1000	0.07%

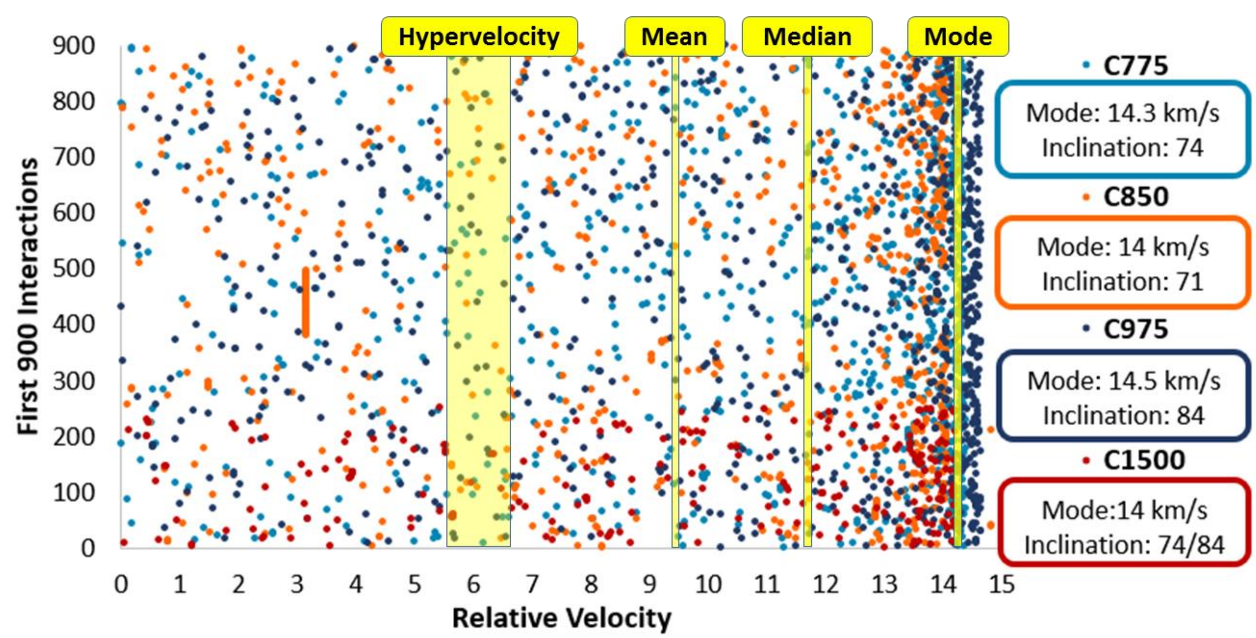
[1] Note that the ½ term appears to insure that we do not double count possible encounters within the cluster.

APPENDIX C: Encounter data for all clusters

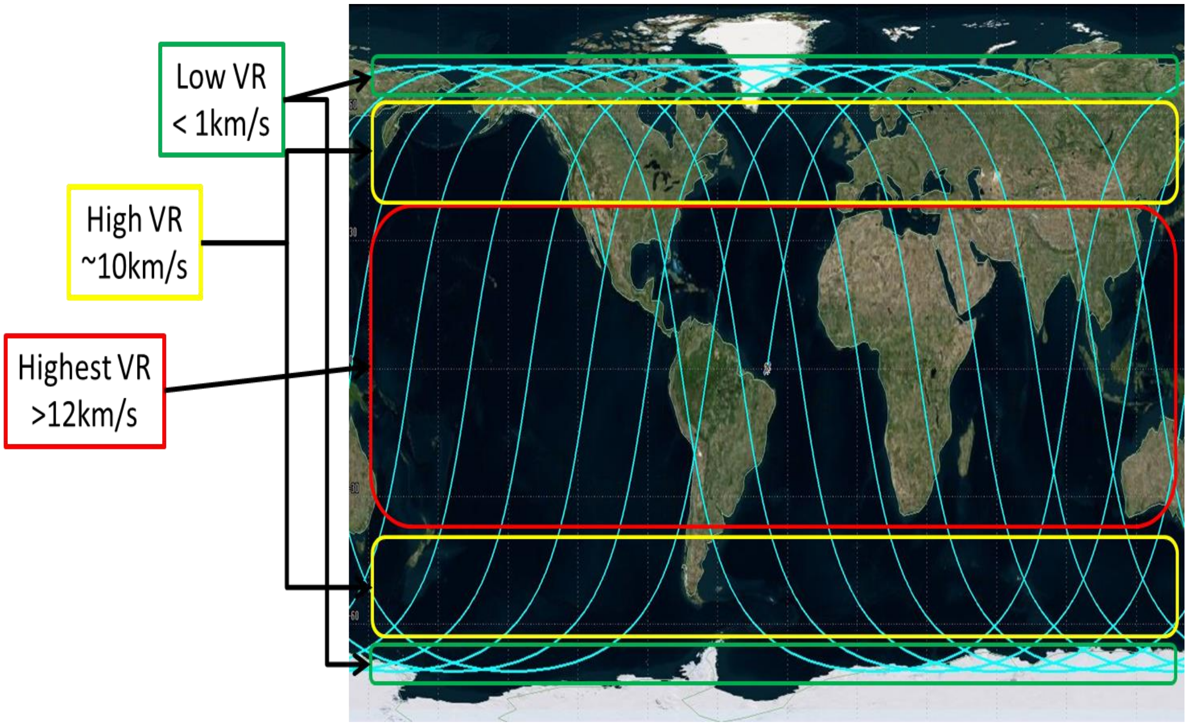
	C775			SL16 R/B Only			C850			C975			C1500		
	<5km	<1km	Closest	<5km	<1km	Closest	<5km	<1km	Closest	<5km	<1km	Closest	<5km	<1km	Closest
Jun 2015				18	0	1146									
Jul 2015				20	0	1971									
Aug 2015				44	3	425									
Sep 2015				12	0	1066									
Oct 2015				9	0	2260									
Nov 2015				25	0	1140									
Dec 2015				15	2	477									
Jan 2016				21	3	447									
Feb 2016				12	0	1178									
Mar 2016				32	2	778									
Apr 2016				19	0	1609									
May 2016				4	0	1113									
Jun 2016				25	0	1080				1786	77	27			
Jul 2016				17	2	946				1762	81	73			
Aug 2016				9	0	1115	49	0	1115	1796	73	64			
Sep 2016				114	2	634	144	3	634	1710	55	65			
Oct 2016				18	0	1936	54	1	750	1803	56	102			
Nov 2016				17	0	1013	38	1	867	1911	89	122			
Dec 2016	211	8	565	18	1	815	50	1	815	2135	94	116	33	3	694
Jan 2017	194	11	176	14	0	1492	48	0	1402	1798	77	190	39	1	459
Feb 2017	155	11	436	32	2	501	82	1	501	1735	76	160	31	3	208
Mar 2017	211	7	200	12	0	1653	46	2	759	1874	76	207	35	1	718
Apr 2017	200	13	135	12	0	2137	54	3	812	1836	71	56	36	2	512
May 2017	212	14	472	14	2	169	46	3	260	1745	75	101	39	0	1358
Jun 2017	201	9	329	26	0	1202	75	3	652	1786	78	122	30	1	202
TOTAL	**1183**	**64**		**384**	**19**		**519**	**15**		**18177**	**900**		**213**	**10**	
Min	155	7	135	4	0	169	46	0	260	1710	55	27	31	0	208
Mean	197	11	331	18	1	1120	65	2	740	1818	75	106	36	2	658
Max	212	14	565	44	3	2260	144	3	1402	2135	94	207	39	3	1358
sigma	20	2	166	9	1	561	32	1	327	115	11	58	3	1	356
#5km/#1km	**18**			**20**			**35**			**20**			**21**		

Total:
20,365: #<5km
1,001: #<1km
246: #<500m

80-90% of all relative velocity values for conjunctions less than 5km for the four clusters exceed the hypervelocity threshold level.



The magnitude of relative velocity of potential conjunctions is also a function of latitude with the events at higher latitudes being much more likely.



The original clusters shown in the panel below on the left cover very focused areas in LEO while the addition of Chigh covers a much broader swath of space in Earth orbit as evidenced in the panel below on the right. The small square in the lower left corner of the right panel depicts where the original four clusters reside.