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Assessing Potential for Cross-Contaminating Breakup Events from LEO to MEO/GEO

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Abstract

The Massive Collision Monitoring Activity (MCMA) was started in 2015 to examine encounter dynamics of clusters of massive objects in low Earth orbit (LEO) that had the potential for significant debris-creating collision events. While this population contributes significantly to the potential for the most risky orbital encounters, it was noted in 2017 that there is a large population of abandoned rocket bodies that both interact with these clusters in LEO and whose orbits extend to medium Earth orbit (MEO, largely semi-synchronous) and geosynchronous orbits (GEO). This cross-cutting population of 180 massive objects (largely rocket bodies) totalling over 500,000kg of derelict mass has been monitored over the last two years to characterize their encounter rates with massive objects in LEO and each other. Results from this analysis are presented showing that, while these objects in highly elliptical orbits have a much lower probability of collision, the consequence of such an event is distinctly severe due to how the resulting debris would pose collision risks to objects across the altitudes that these derelicts' orbits span. This is concerning since it has been shown in the past that the probability of major debris-generating events in GEO (and other higher Earth orbits) is much lower than in LEO but this potentially cross-contaminating population could bridge this large spatial separation. Worst offenders are identified as objects to be removed to significantly reduce the risk from this possible cross-contaminating mechanism and observations are made about close encounter rates (relative to the original LEO clusters). The top 20 worst offenders in LEO includes three objects added to the analysis this year and the top ten worst offenders for the highly elliptical derelicts includes objects from five space launching states. In addition, the 50 closest conjunctions between all massive derelicts monitored over the last two years are analysed relative to the collision risk determined for the Iridium/C2251 collision in 2009.

Keywords: debris risk, collisions, derelicts

1. Introduction

We hypothesize that it is more important to examine immediate space safety risks rather than long-term environmental stability. [1-2] Further, scrutinizing a limited subset of the debris population that will create the most consequential events (i.e., clusters of massive abandoned space objects) provides clarity in risk calculations that may help to prove or disprove this hypothesis. [3-4] Assurance of immediate spaceflight 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 catalogued population over the long term). 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).

In summary, we are striving to break out of the cognitive bias of studying 100yr evolution models, waiting for someone else to develop Active Debris Removal (ADR) solutions, and hoping that massive collisions will not occur. In addition, this year we have included objects in highly elliptical orbits that cross through low Earth orbit (LEO). These objects have been investigated in the past as a uniquely challenging population to monitor and characterize. [5-7]

In contrast, we suggest following a sequence of monitoring and characterizing interactions between clusters of massive derelicts to provide a basis for responsible action (e.g., remove the worst offenders or create an emergency response capability to prevent imminent collisions). This ongoing experiment is called the Massive Collision Monitoring Activity (MCMA).

2. Review of Pure Clusters [8-9]

The clusters identified for the initial MCMA effort in 2015 were selected by considering (1) proximity of apogees and perigees (i.e., clumped in altitude); (2) common inclination values (speculated to cause greater interaction rates and permit more accurate risk calculations); (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). It should be no surprise that the riskiest clusters identified are in LEO due to greater orbital velocities, higher mutual inclinations, and a larger concentration of debris. These criteria resulted in the selection of four "pure" clusters that contain nearly 500 objects of Russian origin that have an aggregate mass of nearly 800,000 kg.

The clusters are named by their centering altitude. For example, Cluster 775 (C775) is centered at roughly 775km altitude. All of these clusters were populated between 1970 and 2007 by the deployment of payloads (PL) to long-lived orbits and abandoning the rocket bodies (RB) that deployed them into similar orbits. Within these LEO clusters 85% of the close approaches (less than 5km) exceed hypervelocity speeds (i.e., 6 km/s) and the median is ~12km/s.

The table below depicts key facts and the encounter rates for a year-long analysis of the four "pure" clusters reported in 2017.

C975 has the greatest number of encounters. This is to be expected since it has the greatest concentration of objects (2.55 objects/km) which yields the greatest predicted collision rate among members of the cluster (1/92 per year). C975 also has a slightly higher immediate risk (~43 vs. ~28) compared to C850 and will have a greater persistence as debris produced in C975 will have a ~4x longer orbital lifetime than debris from a C850 event. While C1500 has the lowest immediate risk, debris generated in C1500 will persist ten times longer than debris produced in C975 and ~40x longer than C850. C775 has the second greatest object concentration of derelicts, but is the lowest altitude cluster, so it has the least persistence. The most consequential collisions would occur in C850; if two SL-16 rocket bodies collide, it would produce around 16,000 trackable fragments, which would double the catalogued population in LEO.

While the Poisson probability distribution is typically used to determine probability of collision and collision rate for orbital debris applications, the gamma distribution predicts the probability of when the first event in a Poisson process is likely to occur and produces the following two observations:

For C975, within which a collision would produce around 4,000 catalogued fragments (and ~40,000 LNTs), there is ~11% chance that statistically such a collision could have already occurred (i.e., cumulative probability).

For C850, within which a collision would generate some 16,000 trackable fragments (and ~160,000 LNTs), there is ~1% chance that statistically such a collision could have already occurred.

3. Expanded MCMA

The original motivation for MCMA was to monitor and characterize a small, but uniquely consequential, subset of the catalogued population with the hypothesis that they pose the majority of the risk for a large debris-generating event. However, while these four clusters are comprised of ~500 massive derelicts amounting to ~800,000kg of mass, there were still hundreds of massive derelicts that were not in "clusters" so their potential debris-generating capabilities were not considered in the original four "pure" clusters monitored in MCMA. The decision to add more objects provided a more complete assessment of the massive derelict population. As a result, over 300 more objects

Table 1. Characteristics of the four "pure" clusters and their interaction dynamics highlight the debris-generating potential of these objects.

	C775	C850	C975	C1500
Total # of Objects	88	36	301	65
Concentration (#/km)	1.29	0.67	2.55	0.32
Total Mass of Objects (kg)	~100,000	~208,000	~335,000	~118,000
Average Mass of Objects (kg)	1,150	5,800	1,150	1,700
# Encounters < 5km per month	197	65	1818	36
# Encounters < 1km per month	11	2	75	2
Calculated Collision Rate/Year	1/413	1/578	1/92	1/1345
Collision Consequence (Trackable Debris Created)	~3,500	~16,000	~4,000	~6,000
Collision "Risk" (Probability x Consequence)	9	28	43	5
Persistence (lifetime, yrs, for 0.01m^2/kg)	~300	~500	~1,800	~20,000

amounting to ~800,000kg additional mass were added to the first four clusters. Any nonoperational orbiting object (1) whose apogee is below 2,000km altitude range and (2) has a mass of over 2,000kg was added to the MCMA experiment. [8-9]

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 original clusters have derelicts added within their altitude range (but previously excluded since they did not have the same inclination value(s) for each of the “pure” clusters).

More space launching states are represented in the “complete” clusters than in the original four clusters, which were all Russian hardware, mostly in matched pairs of rocket bodies and payloads.

Complete Cluster 775 (CC775) contains 101 objects made up of the original 88 objects (C775) and 13 new objects (C775N), including three of the most massive objects in LEO: an SL-16 rocket body, the non-operational Envisat payload, and defunct Russian payload Cosmos 2441. These three objects, added to CC775, are three of the top 25 most massive objects in LEO. CC775 now is comprised of ~150,000kg vice the original ~96,000kg and the average mass increased from ~1,000kg to ~1,500kg. In addition, this cluster now has hardware from Russia, the European Space Agency (ESA), China, and the United States (US).

Complete Cluster 850 (CC850) contains 75 objects, more than double the number of the original 36 objects in C850. However, the objects in C850N are much less massive than the original C850 cluster. The average object mass dropped from ~6,000kg to ~3,500kg, yet CC850 still has the greatest average mass of any of the clusters. The vast majority of CC850 is still Russian, but there are a few objects now from the ESA, China, and the US.

Complete Cluster 975 (CC975) only had 13 new objects added to the original 301 objects in C975. Of these 13 new objects, there is one Chinese rocket body and another SL-16 rocket body.

The new Complete Cluster 1200 (CC1200) only has eight objects averaging 2,000kg with six Russian payloads and two Chinese payloads.

Complete Cluster 1500 (CC1500) is made up of 69 objects, with four objects added to the original 65 in C1500. Two of the four new objects were US payloads and the other two were Russian payloads.

The LEO “Cluster” (Cleo) includes 22 objects whose apogees are less than 2000km and whose orbits span more than one of the clusters. These 22 objects have an average mass of ~3,000kg and comprised hardware

Figure 1. The new set of objects to be monitored and characterized by MCMA provides a more complete coverage of the massive derelict population, now accounting for ~800 objects amounting to ~1,600,000kg passing through LEO altitudes.

from mostly Russia but with a few from the ESA, China, and the US.

Cluster High (Chigh) contains many massive objects that reside in highly elliptical orbits with most being rocket bodies abandoned in geosynchronous orbit (GEO) transfer orbits (GTO) or medium Earth orbit (MEO) transfer orbits (MTO). Chigh contains 180 objects amounting to over 530,000kg; this is an average of ~3,000kg per derelict and ~1/3 of the total mass monitored by MCMA.

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 characterization of potential debris-generating collisions in LEO now include interactions within CC775, CC850, CC975, CC1200, and CC1500 plus their interactions with Cleo and Chigh. It is our hypothesis that there will be statistically fewer encounters with the newly added objects relative to the objects in the four original "pure" clusters.

The total objects monitored within MCMA contain nearly 2/3 of the derelict mass that crosses LEO in its ~800 objects. Expanding the derelict population monitored by MCMA not only increased the total mass (by 100%) and number of objects under examination (by 60%), but also now contains derelicts from all major space launching states.

Overall, the key additions to the MCMA experiment are:

- In CC775, three of the most massive objects in LEO were added: an SL-16 RB, Envisat, and Cosmos 2441.
- In CC975, an SL-16 RB was added.
- The new Chigh grouping comprises 180 objects amounting to ~530,000kg that span LEO and MEO/GEO.
- The total collection of massive derelicts now monitored includes all major space launching states, not just Russia.

The table below summarizes the changes to each cluster and encounter statistics for the latest two-year experiment (1 May 2016 – 30 April 2018). It is important to note that the additional ~300 objects (i.e., 57% increase) were only responsible for a 16% increase in monitored encounters less than 5 km. The lack of response to the additional objects illustrates that the original objects are responsible for most of the massive debris-generating collision risk within LEO.

CC975 continues to be the most active cluster, containing over 40% of the total objects monitored and over 75% of the total encounters (less than 5 km). Alternatively, while CC775, CC850, and CC1500 contain ~13%, ~10%, and ~9% of the total massive objects, they contribute ~11%, ~6%, and ~2% of the total interactions, respectively. Similar trends hold true for encounters less than 1km, CC975 had ~80% of the

Table 2. The encounters involving newly added objects to MCMA (i.e., New Encounters) support the hypothesis that the original four "pure" clusters indeed represent a disproportionate amount of the massive debris-generating collision risk.

	Monitored Derelicts			**Encounters < 5km**		
Cluster	Original # (Added #)	Total Derelicts	% Increase	Original Encounters (New Encounters)	Total Encounters	% Increase
CC775	88 (13)	101	15%	4,958 (1,192)	6,150	24%
CC850	36 (39)	75	108%	1,217 (2,240)	3,457	184%
CC975	301 (13)	314	4%	42,746 (2,146)	44,892	5%
CC1200	0 (8)	8	---	0 (52)	52	---
CC1500	65 (4)	69	6%	849 (69)	918	8%
Cleo	0 (22)	22	---	0 (1,897)	1,897	---
Chigh	0 (180)	180	---	0 (175)	175	---
Total	**490 (279)**	**769**	**57%**	**49,770 (7,771)**	**57,541**	**16%**

total encounters while CC775, CC850, and CC1500 combined had ~19%.

However, as highlighted in previous MCMA research, only the very closest approaches measurably contribute to the aggregate collision risk, so the top 50 closest conjunctions were examined, as shown in Appendix A. It was found that CC975 had 40 of the 50 closest encounters and ~25 interactions with higher probability of debris-generating collision than that of the Iridium-33 and Cosmos 2251 collision in 2009, which produced over 2,500 catalogued objects (likely ~30,000 lethal debris). It is noteworthy that most of the interactions in CC975 involve more mass and a higher relative velocity than the 2009 collision, so more debris would likely be created.

Although the majority of the objects added were in the new Chigh cluster (i.e., ~65%), it only accounted for ~2% of the interactions caused by new objects. However, considering the added consequence of cross-contamination associated with the objects, they should not be overlooked. Compared to Chigh, the new Cleo cluster has a larger proportional contribution to encounters (i.e., ~8% of new objects and ~24% of new interactions less than 5km), but does not carry the same consequence of cross-contamination.

The overall larger screening population for MCMA reduces, but does not eliminate, the possibility that we might miss a highly consequential collision.

4. Worst Offenders

In an effort to avoid catastrophic events, we need to identify the worst offenders in LEO that can be seen as the best candidates for removal from orbit. This process involves characterizing which objects pose the greatest risk to the space environment. Risk is the product of the probability of a potential collision and the consequence if the collision were to occur. There are multiple ways to determine the components of risk, probability, and consequence, as shown in Figure 2 below.

First, probability is determined empirically by scrutinizing (1) closest approaches and (2) tallying the encounter rates for a variety of miss distances (i.e., 5km, 1km, 500m, and 250m). Probability is determined analytically by examining altitude overlap of members of the clusters.

Second, consequence is calculated empirically by considering the relative velocity of the conjunctions during the two-year exercise and the object's mass as

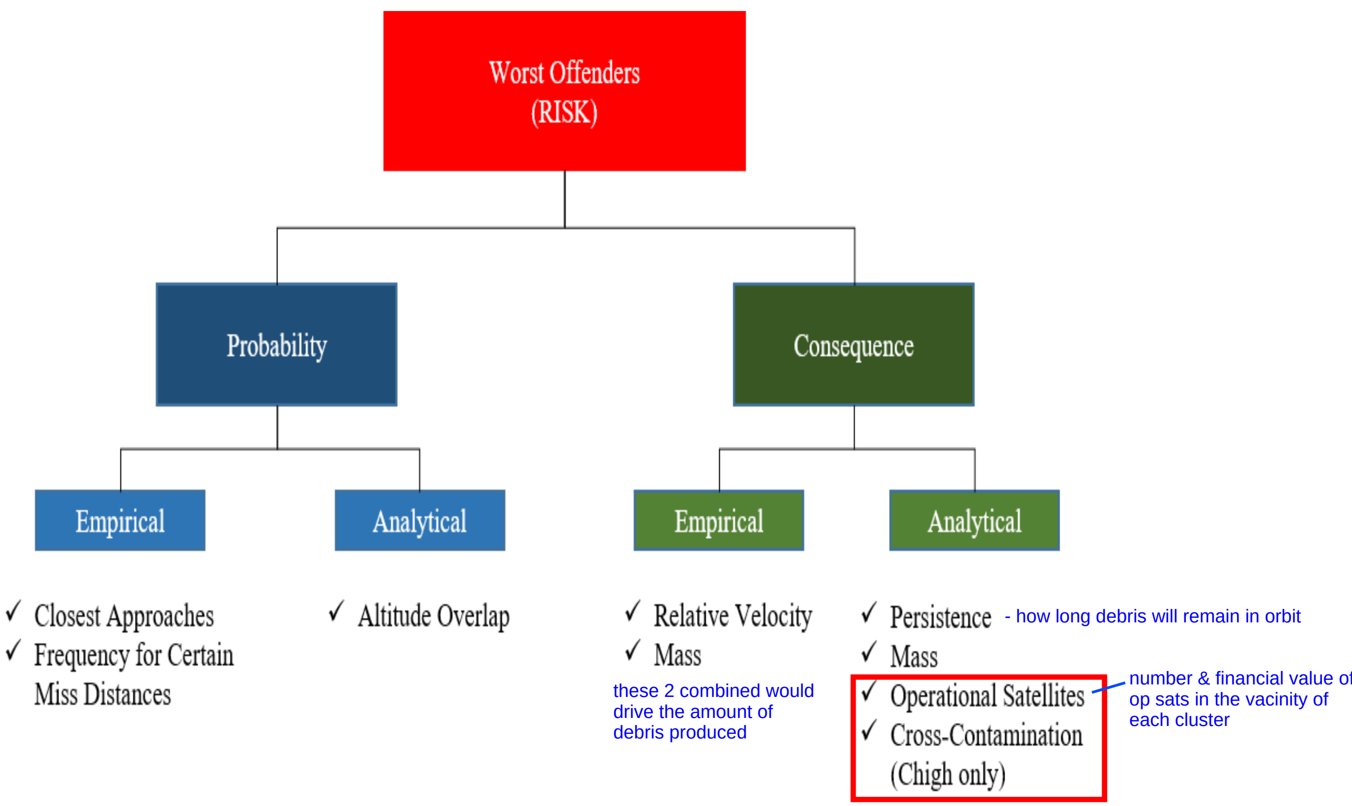

Figure 2. A variety of empirical and analytical assessments were performed to determine the worst offenders (i.e., highest aggregate debris-generating risk).

this combination would drive the amount of debris produced if a collision were to occur. Consequence is also analytically portrayed by persistence (i.e., how long the debris will remain in orbit) and object mass.

Third, a new factor added this year for determining event consequence is number and financial value of operational satellites in the vicinity of each cluster. In the insurance business, the practice of catastrophe modeling is used to predict loss for extremely consequential events that have a low probability of occurring (i.e., natural disasters, terrorist attacks, etc.). Exposure assessment is an important step in predicting catastrophic loss and final determination is made on the basis of density/concentration of people and assets that would be affected by a catastrophic event in that area. [10] The low probability and high consequence of a potential collision between the massive derelicts in MCMA replicates that of a catastrophic terrestrial event such as a hurricane. Therefore, it is critical that we consider both the debris produced and the number/cost of surrounding assets (i.e., operational satellites) that could be affected by a massive collision. The space around CC775 contains over 4x the number of operational satellites than in the vicinity of CC850 and CC975, equating to more than 3x the monetary value of operational satellites, [11] resulting in a more severe exposure assessment.

The last analytical consequence test, cross-contamination, is only for Chigh interactions and will be discussed further in the Chigh section.

After analyzing nearly 60,000 interactions between ~800 massive derelicts over the latest two-year span the top 20 worst offenders were determined and are listed in Table 3.

The top two worst offenders were added to MCMA this year (i.e., are not part of the original "pure" clusters). One of these new objects, satellite number 27006, is an SL-16 RB; it is the clear-cut overall worst offender due to its high mass and location in the dense CC975. The second worst offender is Envisat which has a high mass, like the SL-16 RB, but is located in CC775. Envisat's location in CC775 poses additional risk because, as previously mentioned, CC775 is in close proximity to a larger population of operational satellites, compared to CC850 and CC975.

The remaining objects in the top 20 worst offenders are mostly SL-8 RBs from CC975 and SL-16 RBs from CC850. In addition, a couple of the payloads from CC975 made it into the top 20. In fact, the vast majority of the top worst offenders (i.e., 17 of the 20) are in the original "pure" clusters despite the extended observation period and the tracking of 57% more objects. This once again reinforces that the objects in the original clusters encompass the prominent risk of massive collisions for the entire population. However, the inclusion of Satellite Number 19531 (NOAA 11 payload) is notable as it is the third object in the top 20 that was not part of the original four pure clusters, the fourth payload, and is the only US object on the list.

In reviewing, the top 50 closest approaches and encounter rates, it was determined that removal of the top 20 worst offenders would reduce the overall debris-generating risk in LEO by ~15-30%. A greater emphasis was placed on the very closest approaches and the very tightly overlapping objects. Looking even more closely, the removal of the top five worst offenders would reduce the massive debris-generating potential by 8-10%. While this is noteworthy from a risk-reduction standpoint, it is important to note that with low probability events the most likely event to occur is

Table 3. The top 20 worst offenders primarily are in CC975 & CC850. The bolded objects were included in the top 20 last year, and entries with an asterisk are new objects that were added to MCMA to make "complete" clusters (i.e., were not considered in the previous worst offender analysis.)

Worst Offenders		
	Object	**Cluster**
1	27006 / SL-16 R/B	*975
2	27386 / Envisat	*775
3	**9044 / SL-8 R/B**	**975**
4	**15037 / SL-8 R/B**	**975**
5	**15056 / SL-8 R/B**	**975**
6	22308 / SL-8 R/B	975
7	8646 / SL-8 R/B	975
8	18129/COSMOS 1861	975
9	10732 / SL-8 R/B	975
10	**22285 / SL-16 R/B**	**850**
11	**23405 / SL-16 R/B**	**850**
12	**23088 / SL-16 R/B**	**850**
13	4799 / COSMOS 385	975
14	6708 / SL-8 R/B	975
15	**32053 / SL-8 R/B**	**975**
16	**31793 / SL-16 R/B**	**850**
17	**28353 / SL-16 R/B**	**850**
18	5239 / SL-8 R/B	975
19	19531 / NOAA 11	*850
20	**22566 / SL-16 R/B**	**850**

likely not the next event to occur. This lack of certainty should motivate us to take action rather than paralyze the community into doing more long-term studies. We propose that it is likely that doing nothing may pose a greater risk than starting to be proactive in debris remediation, especially since we have focused the effort on the top five of the most massive and tightly clumped derelicts.

The probability of objects interacting is also highly affected by the degree to which the altitudes of their orbits overlap with each other as per a key worst offender test mentioned earlier. A visualization of this altitude overlap and the date each object was launched into orbit was created to help examine the clusters. Figure 3 depicts what we call the "Stock Ticker" that shows that many of the worst offenders have orbits with close proximity to the average cluster altitude, causing them to overlap with more objects.

The objects in green, with boxed satellite numbers, are the top 20 worst offenders in LEO. The red numbers and horizontal lines indicate the average altitude for each cluster. The "Stock Ticker" shows that CC975 is much denser than the other two clusters. Many objects in CC975 were launched into similar altitudes for the majority of the 37-year span, which explains why the worst offenders in CC975 are spread out across the time period. However, within CC850, the SL-16 rocket bodies did not start becoming a "problem" until 1984 when the objects were launched into more circular orbits due to a change in the primary launch vehicle (i.e., first stage). [12] All of the worst offenders in CC850 were launched after 1984 and all maintain orbits close to the average altitude of the cluster.

Orbits in CC775 maintained a consistent pattern throughout the span, and the only worst offender in the cluster is Envisat. The ~8,000kg satellite has a circular orbit at about 766 km and has been a concern since it became non-operational in 2012. Only two years prior, on 21 January 2010, Envisat performed a collision avoidance manoeuvre to increase the miss distance with a derelict Chinese rocket body. [13] The predicted miss distance was 48m with a radial separation of 15m which resulted in a probability of collision of greater than 1/100. Historically, Envisat has made a number of collision avoidance manoeuvres other than the one just noted; it performed two in 2009, four in 2010, and four in 2011. [14] Envisat still resides in the same orbit, but can no longer perform evasive manoeuvres.

5. Chigh Encounters

Chigh objects are monitored because fragmentations of these massive objects (primarily rocket bodies) would pose a unique cross-contamination hazard between LEO and MEO or GEO. The hardware monitored in the LEO clusters are primarily of Russian origin, however, the 180 Chigh objects comprise objects

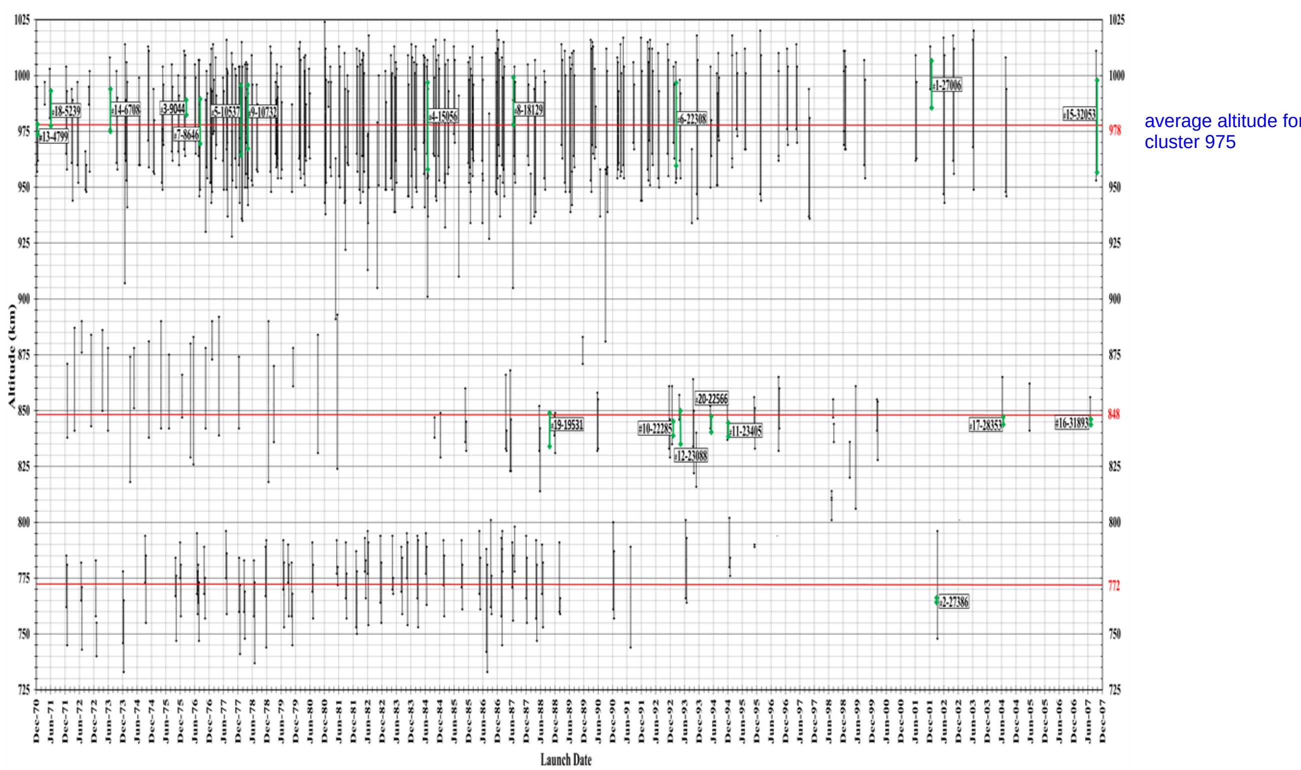

Figure 3. Each vertical line represents the altitude span (i.e., apogee and perigee) for a monitored derelict in clusters CC775, CC850 and CC975 in the "stock ticker."

from the six different launching states/organizations (China, the ESA, India, Russia, Japan, and the US). Of these objects, ~95% are hardware associated with deployments to GEO; the MTO derelicts amount to less than 5% of the Chigh population.

To characterize the cross-contamination hazard from Chigh objects, apogee and inclination must be taken into account. Derelicts with inclinations below 15degrees and apogees within 300km of GEO, of which there are 33, could potentially create direct cross-contamination to GEO operational spacecraft depending on its argument of perigee. The 33 objects that cross GEO orbits at low inclinations were involved in ~11% of the total number of Chigh encounters (i.e., <5km).

For the seven objects with potential MEO cross-contamination, there is no inclination threshold while apogees are within 500km of the semi-synchronous orbit (i.e., 12hr orbital period, where global position, navigation, and timing (PNT) systems reside) is considered hazardous. The seven objects with a higher probability of affecting satellites in semi-synchronous orbit were involved in ~4% of the total number of Chigh encounters. While the objects in LEO are densely clustered, the objects in Chigh are distributed such that a collision involving one of these objects would not be extremely consequential unless the resulting debris would directly interfere with active satellites in MEO or GEO. The relative velocity of these conjunctions were also considered; if less than 6km/s, the collision is considered less catastrophic (i.e., less debris produced). The results of this characterization appear in Figure 4.

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The upper panel of Figure 4 depicts the distribution of conjunctions less than 5 km involving Chigh objects. The square markers represent encounters where both objects are in Chigh and the circular markers represent encounters where a Chigh object gets close to a massive object in LEO. The red markers represent the 19 interactions (<5 km) with the highest consequence, based on relative velocity and the proximity to MEO and GEO (see legend for thresholds). The green markers represent lower consequence interactions (also based on relative velocity and the proximity to MEO or GEO). The yellow markers are interactions that fall between the two defined thresholds.

Of the 175 total Chigh interactions (i.e., conjunctions under 5km), 11 of the encounters were between two Chigh objects, the closest being 1.6km. The three encounters that occurred outside of LEO are particularly interesting. Since these objects have highly elliptical orbits and are randomly distributed relative to each other, they were not expected to have intra-category encounters, especially outside of LEO.

The overall consequence of the interactions between two Chigh objects was found to be low, especially outside of LEO, largely due to low relative velocities of these conjunctions (median of 6 km/s). Despite the lower relative velocities, the unexpected conjunctions show how much uncertainty there is in estimating collision risk from and between objects in highly elliptical orbits.

Chigh's unique orbits require us to determine the worst offenders separately from the clusters in LEO. Table 4 shows the final results for the top ten Chigh worst offenders. The tests that were applied are similar to those described previously and are included in Figure 2 for reference. One of the major changes to this evaluation process was to include the risk of cross-contamination.

The PSLV rocket body is bolded because its collision risk was significantly higher than the other objects on the list. This is because it was the most consequential object on the cross-contamination test and had one of the closest interactions. As expected, the majority of the Chigh worst offenders cross into GEO where collision debris could affect large operational satellites. However, the #1 PSLV and the #9 CZ-3B rocket bodies are positioned so that a fragmentation of either would affect PNT satellites in MEO.

Table 4. The worst offenders for Chigh objects includes rocket bodies from five launching entities: China, the ESA, India, Russia, and the US. The majority of the Chigh worst offenders would affect GEO satellites.

Chigh Worst Offenders		**Orbit Affecting**
1	**40270-PSLV R/B**	MEO
2	6797-ATLAS CENTAUR R/B	GEO
3	39618-ARIANE 5 R/B	GEO
4	26762-BLOCK DM-SL R/B	GEO
5	28138-BLOCK DM-SL R/B	GEO
6	41593-ARIANE 5 R/B	GEO
7	36832-ARIANE 5 R/B	GEO
8	25405-CZ-3B R/B	GEO
9	40750-CZ-3B R/B	MEO
10	10722-ATLAS CENTAUR R/B	GEO

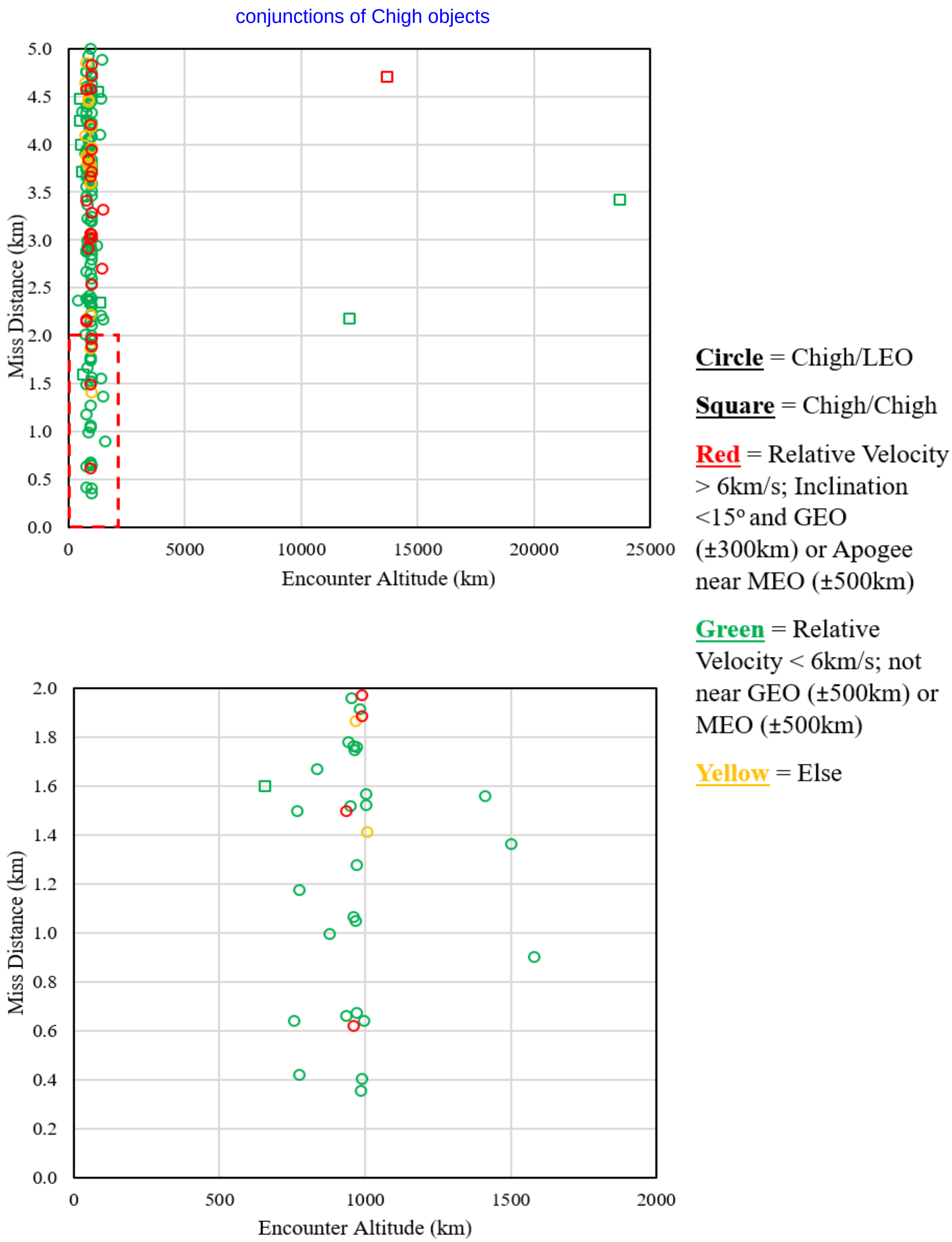

Figure 4. The majority of Chigh cluster's encounters occurred around an altitude of ~1,000 km (i.e., with members of CC975), but three encounters took place as high as 23,000 km (between two Chigh objects).The red dashed rectangle in the upper panel is magnified in the lower panel.

It is important to recognize that rocket bodies from five launching states (China, the ESA, India, Russia, and the US) are on the list of Chigh worst offenders. This reinforces the uniquely international nature of the Chigh collision risk.

Determining the risk for the Chigh objects is complicated due to the dynamic nature of their orbits; due to solar-lunar perturbations, these elliptical orbits are highly dynamic. As a result, this two-year experiment can only be considered a snapshot for Chigh risk where the longer analysis time is relevant for the stable LEO clusters.

6. Summary

The expansion of MCMA not only served to reinforce the previous hypotheses, but it also brought to light additional empirical insights.

First, the MCMA showed that we continue to have close approaches monthly between massive derelicts whose single pass PC values are comparable to values for past high profile collisions between trackable objects in LEO (i.e., Iridium-33 & C2251).

Second, the MCMA experiment exhibits a similar challenge to planetary defense where large consequence, low probability events are difficult to calculate. [15] While we monitor encounters between the most massive objects, it is important to note that the degradation of satellite operations (of exposed subsystems such as solar arrays, communication antennas, and propulsion systems) will be driven by the 10,000s and 100,000s of objects as small as 1mm that would be produced by these massive collisions

Third, 20 worst offenders were identified in LEO whose removal would reduce the potential massive debris-generating risk by ~15-30%. While the removal of the top five worst offenders would reduce the massive debris-generating potential by 8-10%. It is hoped that this observation will serve as a catalyst for the acceleration of debris remediation activities; even the removal of a few objects can measurably reduce the possibility of catastrophic events in LEO.

Fourth, the cross-contamination potential from MTO/GTO rocket bodies is non-trivial. There were three misses less than 500m and ten misses less than 1km between the 180 massive objects in MTO/GTO and massive derelicts in LEO. In addition, there were three unexpected encounters less than 5km between Chigh objects amongst themselves above LEO.

Figure 5 provides a summary of this year's and last year's MCMA research findings.

In summary, the continuing MCMA research has reinforced that the "clusters" are responsible for most of

Reported in 2017	Features	Reported in 2018
~# 500 / ~800,000kg	Derelicts	~#800 / ~1,600,000kg
Four "pure"	Clusters	Five "complete" plus GTO/MTO
One	Years of Data	Two
	#Conjunctions	
~ 25,600	< 5km / yr	~ 28,000
~ 1,100	< 1km / yr	~ 1,200
~ 6	< 100m / yr	~ 12
	KEY OBSERVATIONS	
11% probability of SL8/SL8 collision @ 975km: add ~4,500 1% probability of SL16/SL16 collision @ 850km: add ~16,000 10 worst offenders are Russian rocket bodies at 850km and 975km		"Getting lucky" (i.e., PC ~ Iridium collision) monthly at 975km 180 derelicts in GTO/MTO had 3 encounters < 500m with LEO derelicts Remove 20 worst offenders reduces probability of massive collision by 15-30%; top five reduces risk by 8-10%
4 "pure" clusters have vast majority of encounters; two new objects situated in the middle of CC775 and CC975 are top two worst offenders: Envisat and SL-16 rocket body (#27006).		

Figure 5. The cumulative insights from the ongoing MCMA effort highlight the need for accelerating debris remediation efforts.

the massive collision risk within LEO, and the original "pure" clusters are responsible for most of that risk. However, when it comes to collision risk within the clusters, the SL-16 RB #27006 and Envisat stand above the rest. We propose that the two worst offenders require immediate attention. A collision involving either one of them and one of the many surrounding SL-8 RBs would produce over 12,000 catalogued fragments and 120,000 LNT. In Envisat's case, a collision would scatter debris into altitudes occupied by many operational satellites, potentially causing major financial and technical problems. The next three objects in the top 20 worst offenders list, three SL-8 RBs in CC975, pose a significantly larger hazard than all of the other derelicts monitored: Satellite Numbers 9044, 10537, and 15056.

Similarly, the Indian PSLV R/B #40270 presents substantially more risk than the other worst offenders in Chigh and should also be closely monitored. Due to the dynamic nature of derelicts in highly elliptical orbits, the ability to predict future collisions is very futile, while for the LEO clusters the continual characterization of the conjunctions is leading to a better capability to predict collisions between the massive derelicts up to 3-5 days before an event. This is a topic for further research as it helps to enable more debris remediation options.

The implications of a massive collision in LEO are growing as more countries, and even businesses, become more reliant on space systems. Rather than wait for a collision to add 10,000s additional pieces of debris to LEO, which will only serve to exacerbate the problem, it is imperative that we take this threat seriously and take action. The difficulty of recovery from a collision of massive derelicts accentuates the need to prevent those events with either ADR or just-in-time collision avoidance (JCA). [8-9]

We should heed Benjamin Franklin, who once said, "an ounce of prevention is worth more than a pound of cure."

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APPENDIX A (Top 50 Closest Approaches)

50 Closest Conjunctions												
#	**Primary Satellite**	**Secondary Satellite**	**Range (m)**	**Range (r)**	**Range (i)**	**Range (c)**	**Velocity (km/s)**	**Primary Cluster**	**Secondary Cluster**	**Primary Mass**	**Secondary Mass**
1	11165--COSMOS 1066	19531--NOAA 11	**10.4**	-2.4	5.9	-8.2	**12.1**	850N	850N	2750	1,710
2	10537--SL-8 R/B	16510--COSMOS 1727	**26.6**	4.1	12.4	-23.2	**13.0**	975	975	1434	810
3	20232--COSMOS 2038	21728--COSMOS 2157	**31.2**	0.0	-16.0	26.8	**12.2**	1500	1500	2477	2,477
4	14084--COSMOS 1464	27006--SL-16 R/B	**34.9**	-6.6	2.5	34.2	**14.7**	975	975N	810	8,900
5	21902--COSMOS 2181	10531--COSMOS 970	**45.8**	38.6	-7.2	-23.7	**14.2**	975	LEO	825	3,320
6	9044--SL-8 R/B	9737--COSMOS 890	**46.1**	-44.9	-3.0	9.8	**14.0**	975	975	1434	700
7	22823--SPOT 3	19120--SL-16 R/B	**53.8**	-36.3	9.9	38.4	**14.4**	850N	850	1907	8,300
8	9610--COSMOS 883	22006--COSMOS 2195	**55.6**	-20.4	12.8	-50.1	**14.3**	975	975	700	825
9	11425--COSMOS 1110	18095--COSMOS 1850	**61.7**	27.4	17.9	52.3	**14.1**	775	775	850	850
10	7769--SL-8 R/B	17066--COSMOS 1791	**64.7**	63.7	-1.2	11.1	**14.6**	975	975	1434	810
11	24773--SL-8 R/B	17159--COSMOS 1802	**69.7**	-67.6	13.6	-10.3	**9.1**	975	975	1434	810
12	6149--SL-8 R/B	10020--SL-8 R/B	**72.5**	42.3	15.4	-56.8	**14.2**	975	975	1434	1,434
13	8421--SL-8 R/B	18709--COSMOS 1904	**72.7**	54.7	9.0	-47.0	**14.5**	975	975	1434	810
14	8073--SL-8 R/B	21797--SL-8 R/B	**73.7**	57.9	31.2	33.3	**10.7**	975	975	1434	1,434
15	8597--SL-8 R/B	10776--COSMOS 1000	**76.6**	65.0	8.2	39.6	**14.4**	975	975	1434	700
16	13916--COSMOS 1447	24677--COSMOS 2336	**82.0**	-1.4	14.1	80.8	**14.4**	975	975	810	795
17	14241--SL-8 R/B	11573--COSMOS 1140	**84.4**	74.8	27.9	27.5	**10.3**	775	775	1434	850
18	22693--SL-14 R/B	27055--COSMOS 2384	**88.5**	9.5	64.1	-60.3	**9.8**	1500	1500	1407	2,477
19	19826--COSMOS 2004	32052--COSMOS 2429	**88.5**	-43.7	60.9	47.1	**9.0**	975	975	810	795
20	6829--SL-8 R/B	15085--COSMOS 1579	**93.1**	-66.2	-35.3	55.1	**12.4**	975	975	1434	1,295
21	25569--SL-8 R/B	22590--COSMOS 2239	**99.3**	-97.0	-14.9	15.1	**10.6**	975	975	1434	825
22	9044--SL-8 R/B	10459--COSMOS 962	**100.6**	-93.5	14.0	34.2	**13.6**	975	975	1434	700
23	23604--SL-8 R/B	11378--COSMOS 1104	**101.7**	87.7	6.1	-51.2	**14.6**	975	975	1434	700
24	7594--SL-8 R/B	9610--COSMOS 883	**110.9**	12.4	-67.2	-87.3	**11.7**	975	975	1434	700
25	15752--SL-8 R/B	15359--COSMOS 1605	**111.1**	95.4	28.1	49.3	**12.8**	975	975	1434	810
26	10459--COSMOS 962	18957--COSMOS 1932	**112.2**	-108.8	18.6	20.3	**10.8**	975	975	700	1,295
27	10537--SL-8 R/B	18710--SL-8 R/B	**118.4**	-46.4	-29.8	104.8	**14.1**	975	975	1434	1,434
28	37214--FENGYUN 3B	16182--SL-16 R/B	**119.4**	-110.5	36.6	26.6	**8.6**	850N	850	2234	8,300
29	11736--SL-8 R/B	5238--COSMOS 422	**119.7**	113.7	-15.0	-34.2	**13.5**	975	975	1434	700
30	7094--COSMOS 628	17359--COSMOS 1816	**122.0**	119.9	-5.9	-21.7	**14.1**	975	975	700	810
31	10693--SL-8 R/B	11378--COSMOS 1104	**124.7**	13.1	-32.0	-119.8	**14.2**	975	975	1434	700
32	20804--COSMOS 2100	13600--COSMOS 1412	**124.9**	-89.6	25.8	83.1	**14.1**	975	975	825	1,295
33	6019--COSMOS 489	10019--COSMOS 911	**125.9**	-125.9	-1.3	-2.2	**13.8**	975	975	700	700
34	13111--SL-8 R/B	26818--COSMOS 2378	**128.2**	-127.7	1.6	11.2	**14.5**	975	975	1434	795
35	9044--SL-8 R/B	10693--SL-8 R/B	**128.6**	44.0	-41.8	113.3	**13.8**	975	975	1434	1,434
36	16494--SL-8 R/B	23466--SL-8 R/B	**129.3**	-61.1	-19.9	112.2	**14.5**	975	975	1434	1,434
37	11735--COSMOS 1168	14084--COSMOS 1464	**130.3**	30.7	103.3	-73.2	**8.5**	975	975	700	810
38	20104--SL-8 R/B	21087--INFORMATOR 1	**132.4**	3.8	-56.8	-119.5	**13.3**	975	975	1434	825
39	35946--WORLDVIEW 2	8923--COSMOS 836	**134.1**	-121.6	-47.9	-30.2	**7.9**	775N	775	2385	850
40	12443--SL-8 R/B	8458--COSMOS 783	**134.6**	83.5	-87.0	59.8	**8.5**	775	775	1434	850
41	10962--SL-8 R/B	5705--COSMOS 468	**139.7**	-127.5	50.5	27.0	**7.0**	775	775	1434	850
42	23466--SL-8 R/B	26818--COSMOS 2378	**144.0**	44.2	61.0	122.7	**13.1**	975	975	1434	795
43	8646--SL-8 R/B	12091--COSMOS 1226	**158.2**	47.8	135.1	-67.1	**6.5**	975	975	1434	700
44	11321--SL-8 R/B	23180--SL-8 R/B	**158.9**	-63.0	-102.8	-103.6	**10.4**	975	975	1434	1,434
45	4784--SL-8 R/B	15077--COSMOS 1577	**160.7**	154.9	36.9	-21.6	**7.5**	975	975	1434	810
46	8646--SL-8 R/B	10536--COSMOS 971	**160.9**	-115.3	-14.6	111.3	**14.6**	975	975	1434	700
47	21937--COSMOS 2184	22487--COSMOS 2233	**161.2**	-66.5	-117.1	-88.7	**8.9**	975	975	825	825
48	13917--SL-8 R/B	20528--SL-8 R/B	**163.0**	-3.3	-20.9	-161.6	**14.6**	975	975	1434	1,434
49	24677--COSMOS 2336	28380--COSMOS 2407	**164.4**	163.6	-8.6	-14.0	**12.5**	975	975	795	820
50	20508--NADEZHDA 2	18957--COSMOS 1932	**165.1**	-147.3	53.3	52.0	**10.4**	975	975	1434	1,295