APPROACHES TO NEAR TERM COLLISION RISK ASSESSMENT

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ABSTRACT

This paper examines prompt consequences of collisions among objects and satellite explosions in Earth Orbit. We present new techniques for the most likely collisions, which do not involve the entire mass of the objects. We examine collisions in Geostationary and highly inclined orbits. Our test cases are the recent close approach of Intelsat 702 and Raduga 1-7 and the precedent setting collision of Iridium 33 and Cosmos 2251.

1. INTRODUCTION

The objectives of this paper are to apply a technique for assessing operational risk considering both the likelihood of occurrence and the estimated consequences of a conjunction. The threshold of concern for orbital conjunctions is very small because the consequences both to the orbital environment and to critical missions are unacceptable. In the long term, each event increases the on orbit debris population whose distribution and evolution have been investigated in depth. Long term collision risk is an important mission and spacecraft design consideration. Near term consequences, before the debris field attains a stable, long term distribution, are most important but seldom examined. Even though models of instantaneous fragmentation are all arguable, it is useful to have a reasonable, physics-based description of the phenomena that can be used to estimate the early phases of debris dispersion, to assess the likelihood of subsequent conjunctions when the debris may be concentrated, and to bound regions in which large fragments might reenter in the short term. We have developed such models and applied them to real, near term situations.[i] This presentation will examine near term consequences of potential conjunctions of current interest throughout all orbital regimes from LEO to GEO using these techniques. We will share observations in the use of such models, particularly issues associated with conjunctions in the Geostationary Belt, where relative velocities can be small and close approaches might still have low probability of actual body-to-body contact. Debris generated in GEO can permeate all orbital regimes. We also stress the need for widely available tools and techniques that can be employed quickly by operational personnel as opposed to complex numerical schemes that can be employed by a select few initiated in the details. To encourage comment, discussion, and technical progress, we will stress recent events as of the date of the Conference, including the recently publicized Intelsat 709-Raduga 1-7 conjunction in GEO in November 2008 and the Iridium 33 – FY 1C debris conjunction in Feb 2009 for which no such analysis was available.

2. ORBITAL DEBRIS ANALYSIS

Estimating orbital debris event consequences taxes all aspects of astrodynamics and fragmentation science. Operationally useful assessments must be based on accurate and precise knowledge of the states of resident space objects. It is widely recognized that the world's space surveillance capabilities are insufficient for several of the tasks addressed in this paper.[ii] There are not enough sensors, and the manner in which they observe satellite motion and report those observations is inconsistent and non-uniform. The manner in which those observations are transformed into orbit data for propagation into the future should also be improved. The reader may observe from the analyses to follow that available orbit data is often so old that orbit propagation farther into the future is untrustworthy for some applications. Even if the orbit data were completely trustworthy and well characterized, the science of probabilistic conjunction assessment is often not well applied.[iii] Beyond these, fragmentation of ductile or brittle bodies is a physical mystery. Part of our research was exploring the genealogy of fragmentation models, mainly in the munitions effectiveness community but also in other applications, such as blasting in mines. We have also modified our current best of breed breakup model tool suite to enhance the fidelity with which mass and energy are conserved and restore the threads to the origins of these models in the fragmentation science community. [iv,v]. Finally, fragments must be propagated with astrodynamics tools at least comparable to those used to project the debris event. There can be thousands of fragments. This does not mean that every single fragment need be tracked, but abstracting the fragment distribution and estimating subsequent encounters is still an immense task.

2.1 Orbital Debris Work Flow

The process begins with the best information available about the states of objects in orbit. Using a reasonable set of constraints, we employ the CSSI SOCRATES capability to find the most likely encounters based on the maximum probability concept to be described shortly. This technique estimates the probability that two objects will contact, body-to-body, if their osculating orbits are within a specified threshold of each other (usually 5 km). We always use the state at closest approach as the source of energy and momentum for fragments. We apply the DEBBIE breakup tool suite to generate individual fragment parameters and orbital

Proc. '5th European Conference on Space Debris', Darmstadt, Germany
30 March – 2 April 2009, (ESA SP-672, July 2009)

states. Different models apply to explosions than to collisions, although each collision is a combination of collisional and explosive phenomena. We then propagate the debris distribution into the near future. We can again assess collision probabilities between fragments and the extant space object catalog. Since the theoretical fragment set is but one realization of myriad statistical possibilities, seeking collisions between discrete elements of the fragment set and real objects in the catalog is arguable. We are investigating an approach based on unscented Kalman filters[vi] to assess the probability of cascading.

The Socrates technique for determining the probability of body-to-body contact developed by Alfano and Kelso is well described in the literature[vii]. Chan describes the underlying mathematics in his recent book. If the statistics of the two bodies are independent, the covariance of one body with respect to the other in barycentric coordinates is the sum of the two independent covariances in the inertial frame. This reduces the problem to determining the volume of the combined covariance ellipsoid contained within a tube whose cross section is the maximum extent of one body circumscribed about the other. The fact that the event occurs rapidly with respect to changes in either orbital velocities or covariances makes the tube straight. This volume is called a Rician Integral, and it appears often in communication research.

When the orbits are known precisely, the probability of collision is small. The objects digress little from their mean orbits. When the orbits are specified imprecisely, the probability of collision is also small. The objects could be anywhere within their large uncertainty volumes, and the likelihood of their being in the same place at the same time is small. Alternatively the volume of the combined covariance ellipsoid contained within the collision tube is a small fraction of the total volume. This means that there is a value of the combined covariances for which the probability of body-to-body contact is a maximum. This requires no knowledge of the true covariances, but it is a very optimistic estimate. The true probability might be orders of magnitude less. In addition, the probability computation depends on the cross sections of the bodies normal to the conjunction axis. This is often simplified to an elliptical cross section with aspect ratio equal to the ratio of the largest orthogonal dimensions of the objects. Often we do not know this either. SOCRATES treats all conjunctions as though the cross sections were circular, aspect ratio unity. Nonetheless, events with a high maximum probability are subjectively the most threatening for this state of knowledge. We refer the reader to the references for greater depth.

The fundamentals of fragmentation grew obscure as interest in space debris grew even though that science predates space operations by more than a century. There is a great deal of empiricism, but the relationships among material or structural characteristics and fragment size and mass distribution are based on sound physical reasoning. The essential observation is that fracture and fragmentation occur as a stress relief mechanism. The energy of the fragments depends on strain energy stored in the materials as a result of the impact. Maximum entropy principles very similar to those in statistical mechanics reveal physical consequences confirmed by experiments such as the Poisson distributions of fragment sizes and the binomial distribution of likely fracture sites. The two most important underlying facts are that there is a fundamental minimum fragment size determined by the microscopic structure of the materials and that the size scale of larger fragments depends on the possible distribution of stress concentrations and fracture sites, determined by the characteristics of the overall structure. The distribution should be bimodal, the particular velocities of the fragments are due to strain energy release, and (at least for ductile materials) the fragment size distribution should have a definite cutoff at a minimum fragment size.[viii] The approaches of Chobotov and Spencer[ix], Yasaka[x], and the others as modified in our previous paper satisfy these observations.

Head on full body-to-body contact with all of the mass of both objects involved is highly improbable. Since most of the cross section of most satellites is low density solar panels, grazing collisions that directly involve only a fraction of the mass of each body are most likely. Accordingly, the DEBBIE model we invoked in this study utilizes the concept of involved and non-involved masses. The involved masses intermingle in a physics-based, collision-induced fragment distribution. The remainder simply "breaks off" since the fragmentation process resulting from propagating stress waves takes longer than the collision lasts at these velocities. However, the energy so transmitted eventually precipitates further disassembly but with different momenta, generally indicative of the momentum that fraction of the original object had before collision. DEBBIE permits the user to specify the amount of linear momentum exchanged between the involved and non-involved mass fractions.

Initially, it was advocated that the involved mass would fragment in a velocity distribution centered about the pre-collision involved center of mass (Chobotov and Spencer[9]). We now refine this further by introducing the concept of "ghosted" collisions. In ghosted collisions, both the involved and the uninvolved mass fractions of each satellite pass right through each other as described. Conversely, in non-ghosted collisions, the pre-collision combined center of mass of the original two objects is retained as the post-collision center of mass of all involved fragments, whereas the uninvolved fragments disperse about the pre-collisional satellite linear momentum (adjusted for any user-specified momentum exchange as mentioned above).

Upon comparing the "ghosted" and "non-ghosted" approaches with collision fragmentation events, we find that "ghosting" represents more faithfully observations of real world events. We also find that when the masses of the two objects are greatly different, a very small degree of involvement of the heavier object is appropriate. All estimated outcomes that follow are "ghosted."

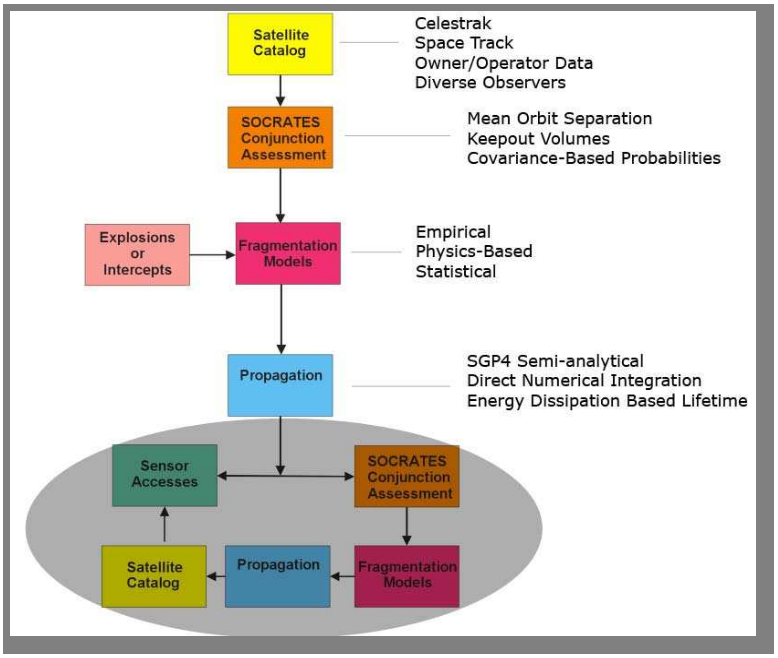

Figure 1: Modls in the Debris Consequence Work Flow

Fig. 1 illustrates our work flow and the kinds of models and data sources that may be employed in the end-to-end analysis of space debris events.

There are many uncertainties. Satellite orbit information is deficient. Orbit data that is available omits essential elements of information such as covariances. Propagation beyond a few days or weeks is uncertain for many (not all) classes of orbits. Fragmentation is an uncertain science. When fragments do eventually decay and reenter the Earth's most dense atmosphere, aerodynamics and the state of the atmosphere are unknown. The bottom line is that this is the best we can do at present and that some approximation to short term consequences of debris events is absolutely essential. It is essential to guide application of scarce resources to the most threatening events. It is essential to plan operational mitigations such as maneuvering only when it is absolutely essential, preserving mission lifetime. It is necessary to estimate risks to life and property on the surface of the Earth. We do not claim that our specific choice of models is best for all circumstances. We encourage readers to develop alternatives. Our objective is to recommend a work flow and share our experience.

3. INTELSAT 702 AND RADUGA 1-7

As conjunction assessment and debris modeling mature, we're revisiting the possible consequences of past events. An estimated conjunction between Intelsat 702 and Raduga 1-7 on 25 Feb 09 attracted attention because Intelsat planned maneuvers but did not know precisely where Raduga 1-7 would be. The closest approach predicted was 23.6 km at 25 Feb 2009 01:48:40.322. Using the states of both objects at that time we estimated the degree of contact that might have existed considering the geometries of both satellites. Considering the age of the satellites and the amount of propellant that might have been expended, we assumed that Intelsat mass was 3000 kg and Raduga mass was 2000 kg. Using the Evolve 4.0 model modified to conserve mass, we assumed that 40% of the mass of each satellite was directly involved in the conjunction. There are also assumptions about the amount of orbital energy non-conservatively transformed into entropy (heat, radiation, etc.) and into kinematics of the individual fragments (spinning, for example). Under these assumptions the models predict 396 fragments with mass greater than 100 grams and UHF RCS greater than -20 dbsm. The latter is a good estimate of the ability of SSN radars to detect an object in normal operations. We propagated the fragments for three days.

Next we looked for subsequent collisions between debris fragments and other communication satellites. There were two: a 1.48 kg fragment hit INSAT-4B at 26 Feb 2009 01:18:47 producing 89 fragments, and a 9.08 kg fragment hit ZhongXing-6B at 26 Feb 09 23:38:35 producing 111 fragments. INSAT mass was assumed to be 2500 kg, and ZhongXing was assumed to be 4000 kg. These masses were inferred from open literature and the time on orbit. Since the fragments are so much smaller than the targets, the fragments were fully involved while at most ten percent of the target mass was involved. The conjunction threshold was 10 km.

The following is a snapshot from the end of the scenario.

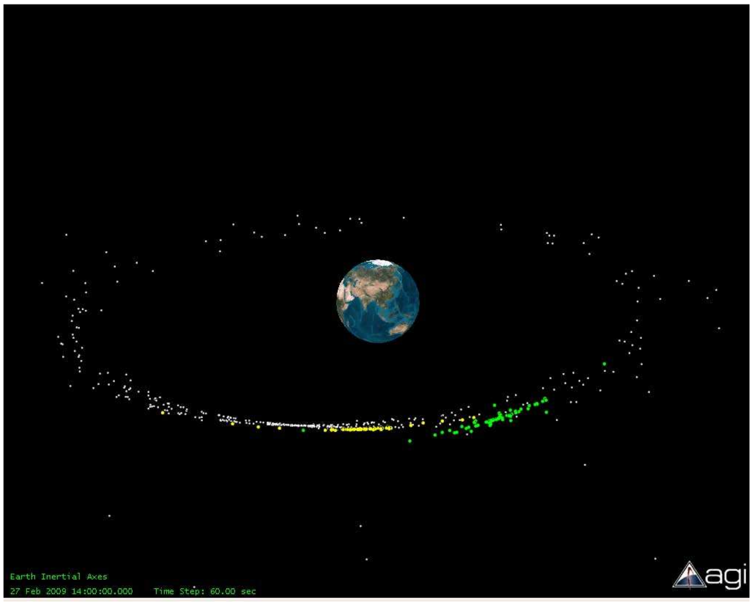

Figure 2; Intelsat 702 – Raduga 7 and subsequent cascading to Insat 4-B and ZhongXing-6B as of 27 Feb 2009, 14:00 UTC. Initial collision at ZhongXing-6B.

White fragments are from the original collision, yellow are from the INSAT collision about a day later, and green are from ZhongXing yet a day later. The size of the dots in no way represents the actual sizes of the fragments. The dots for a given conjunction are all the same size, the fragments are not.

These analyses impart to the fragments only initial orbital energy at most. We can also add energy stored in propellants, momentum wheels, and batteries, aggregated into a single energy release. One gigajoule is a reasonable approximation for a satellite like Intelsat 702. We examined the effect of stored energy release without any collision. We exploded 702 at 1400 on 25 Feb 09. In this case the entire mass was involved and 248 fragments larger than 100 grams were produced. The first subsequent collision was a 0.82 kg fragment with Ekran-1 at 26 Feb 09 18:50:00 producing 1036 fragments more massive than 100 grams. A snapshot of the mature scenario is below:

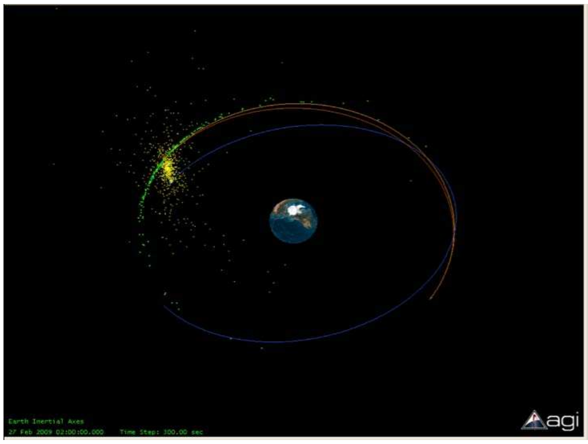

Figure 3. Consequences of Intelsat explosion on 25 Feb 09 14:00 and subsequent cascade to Ekran-1. The original explosion is in green, and the secondary collision is in yellow

This is offered as food for thought. Rest assured that this event is extremely unlikely. What seems to be likely is that such a primary event would within few days lead to additional collisions and debris, emphasizing the extreme diligence required for safe geostationary operations. Additional data, including mass, RCS, and orbital parameters of all fragments at inception are available from the authors.

4. IRIDIUM 33 AND COSMOS 2251

This event attracted attention world-wide and is still a significant concern. For the record, CSSI did predict this event. SOCRATES on the web includes a search utility that reveals all conjunctions a given satellite might experience based on orbit data current to less than 12 hours. Although this conjunction was not in the top ten closest approaches or most likely conjunctions, it was accessible to all through the search utility. That it did not make the top ten can be attributed to (1) using maximum probability based on spheres of unit aspect ratio, (2) poor quality and latent orbit data, and (3) the absence of covariance information. We conjecture that in a more collaborative environment and with more diligent management of the observation processes and orbit determination, this event might have been prevented.

The first order investigation examined how many fragments might have been created. We investigated different degrees of involvement, invoking the minimum fragment size and partial degree of involvement principles. Figure 4 shows the variation of fragment number with degree of involvement. We assumed initial Iridium mass of 600 kg and initial Cosmos 2251 mass of 800 kg.

Figure 4: Iridium 33 – Cosmos 2251 fragment production. Minimum fragment mass 10 grams. Equal degrees of involvement for both objects.

Almost all of the debris is concentrated in orbit bands close to those of the original satellites (86 deg for Iridium, and 72 deg for Cosmos). There is more Cosmos debris because Cosmos initial mass is greater. There can be no more fragments than for complete involvement whether the objects are equally involved or not. Therefore we would expect approximately 554 Iridium fragments and 689 Cosmos 2251 fragments at most. If we use the now slowly growing number of objects observed and cataloged, 40% involvement appears most likely, although the degree of involvement is undoubtedly not the same for both objects. Figure 5 shows the mass distributions of particles attributed to each satellite. The source of involved elements was attributed to inclination bands near those of the original satellites. It is very likely that some of the mass originally in one satellite could reside in the orbit of the other, however.

Figure 5: Fragment Mass Distributions

The next order of business is to assess the consequences of conjunctions with documented and cataloged debris from this event. We have been doing this daily, issuing consequence reports to interested parties. In the space remaining, we will present examples of these reports. At the time of this writing, five conjunctions are predicted. We assessed the fragment distribution using uniformly a 5 kg fragment mass. As seen above very few fragments have masses of even 1 kg, and it is unlikely that the very few very high mass fragments will be involved in other conjunctions. Figure 6 is a snapshot of the totally evolved consequences. The colors given in Table I refer to that snapshot.

Table 1: Predicted Conjunctions

Involved Satellite	Debris Element	Conjunction Epoch	Frags	Color	Type
Iridium 06/10%	Cosmos 34015	11 Mar 09 00 24 UTC	193	Magenta	II
Cosmos 1867/5%	Cosmos 34054	11 Mar 09 10:24 UTC	278	Aqua	II
Fedsat/50%	Iridium 34105	13 Mar 09 03:18 UTC	68	Red	III
Cosmos 1818/5%	Iridium 33950	13 Mar 09 13:20 UTC	278	Yellow	II
Envisat/2%	Cosmos 33770	14 Mar 09 08:01 UTC	626	Green	IV

Type I = Small Cosmos debris with Iridium
Type II = Small Cosmos debris with Cosmos
Type III = Small Iridium debris with Cosmos
Type IV = Small Cosmos debris with Other
Type V = Small Iridium debris with Iridium (unlikely)

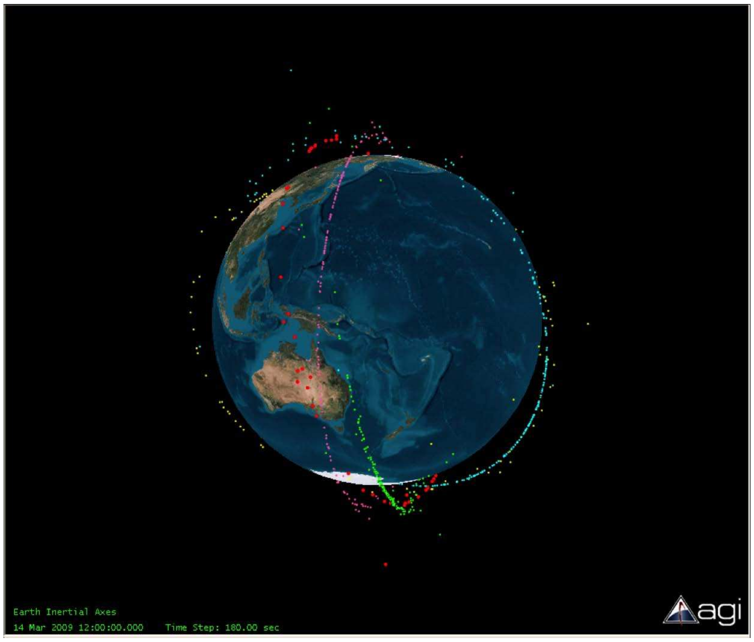

Figure 6: Evolved Consequences of Iridium 33 – Cosmos 2251 Debris Conjunctions, 11-14 March 2009

We find it particularly important that over this time period there are nine estimated close approaches of Envisat with event debris. Because of this, we present the Gabbard diagram for this estimated event as a final example of the analysis technique and products.

Fragments from Envisat – Debris 33770 Conjunction (Gabbard Plot)

Figure 7 is a common depiction, although it does not discriminate objects by inclination, RAAN, or any other orbital quantity. Circular orbits are the (nearly) straight line. Objects will eventually slide down the slope and decay to shorter and shorter periods until they reenter. Our models predict a few debris fragments in very high orbit.

5. COSMOS 494 – COSMOS 2251 DEBRIS 34389

This paper is an evolving record and assessment of recent events. As the debris from the Iridium 33 – Cosmos 2251 collision evolves, other satellites may be jeopardized. At this writing 217 fragments from Iridium 33 and 457 fragments from Cosmos 2251 have been cataloged. Most are in the orbits of the original satellites. All of this is consistent with our theoretical estimates for about 40% mass involvement. Evidence accumulates that this was a grazing collision, and two large Iridium 33 fragments are in close trail near the state that the original satellite would have had. Fragments in nearly the original satellite orbits are not a significant threat to other satellites in similar orbits and inclinations since relative velocities are quite low.

We have begun to issue daily reports of consequences of estimated conjunctions with Iridium 33- Cosmos 3251 debris. For consistency, we always assume that the mass of the debris fragment is 5 kg. The degree of involvement of the larger collision partner depends on its geometry. When the preponderance of the largest cross section is solar panels, we assume 10% involvement or less.

The particular conjunction examined in this section involves a very compact satellite. Cosmos 494 has conformal solar panels; therefore, a collision would involve more of the satellite mass than otherwise. We assumed 20% mass involvement, leading to a much lager fragment count than for prior estimated conjunctions. There were 1761 fragments more massive than one gram.

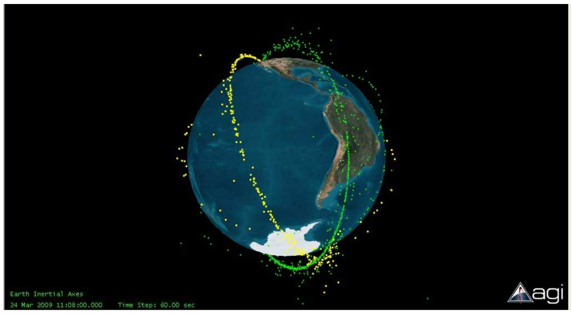

Figure 8: Cosmos 494 – Cosmos 2251 Debris 34389 conjunction (Green) and prior RapidEye- Cosmos 2251 Debris 34034 (yellow)

RapidEye 05 (50%) – Cosmos 2251 34034
20 Mar 09 07:41 UTC
707 Frags
(Type IV RapidEye orbit)

Cosmos 494 (20%) – Cosmos 2251 Debris 34389
23 Mar 09 07 :08 UTC
1721 Frags
(Type II: Iridium orbit)

The distribution of 50 most massive fragment is in Figure 9.

Figure 9: Fifty most massive fragments of Cosmos 494-Cosmos 2251 Debris 34389 conjunction.

This conjunction is unique because both objects are at nearly the same inclination. Generally we can discriminate between fragments from each collision partner by inclination. In this case, the discrimination is best done with right ascension of the ascending node (RAAN). Figure 9 is the Gabbard Plot for this collision at inception.

Gabbard plot.

As expected, the total mass in the original debris orbit is less than 5 kg.

To illustrate the spectrum of information, Figure 10 is the distribution of collision induced debris velocities.

Figure 11: Collision induced fragment velocities

These estimated outcomes guide mitigations and prioritization of predicted events.

6. CONCLUSION:

We have applied recently developed work flows and models to estimating the consequences of conjunctions in Geostationary and lower orbits. Although fragmentation models are arguable, we feel that assessments such as those presented in this paper are meaningful guidance for collision avoidance and consequence management.

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