Consideration of Collision "Consequence" in Satellite Conjunction Assessment and Risk Analysis

M. Hejduk,[1)] F. Laporte,[2)] M. Moury,[2)] L. Newman,[3)] and R. Shepperd[4)]

[1)]*Astrorum Consulting LLC, Woodway, TX USA*
[2)]*Centre Nationale d'Études Spatiales, Toulouse, France*
[3)]*NASA Goddard Space Flight Center, Greenbelt Maryland USA*
[4)]*The Boeing Company; Leesburg, Virginia USA*

(Received June 21st, 2017)

Classic risk management theory requires the assessment of both likelihood and consequence of deleterious events. Satellite conjunction risk assessment has produced a highly-developed theory for assessing collision likelihood but holds a completely static solution for collision consequence, treating all potential collisions as essentially equally worrisome. This may be true for the survival of the protected asset, but the amount of debris produced by the potential collision, and therefore the degree to which the orbital corridor may be compromised, can vary greatly among satellite conjunctions. This study leverages present work on satellite collision modeling to develop a method by which it can be estimated, to a particular confidence level, whether a particular collision is likely to produce a relatively large or relatively small amount of resultant debris and how this datum might alter conjunction remediation decisions. The more general question of orbital corridor protection is also addressed, and a preliminary framework presented by which both collision likelihood and consequence can be jointly considered in the risk assessment process.

Key Words: Conjunction Assessment, Consequence, Kaplan, Debris

Nomenclature

A	:	satellite frontal area
B	:	ballistic coefficient
C_D	:	drag coefficient
e	:	unit vector in velocity direction
L_c	:	characteristic piece length
M	:	mass of heavier (or single) satellite
m	:	mass of lighter satellite
P	:	collision quasi-momentum
P_c	:	probability of collision
V	:	velocity
ρ	:	atmospheric density
Subscripts		
r, rel	:	relative quantity between two satellites

1. Introduction

While the theory and practice of risk assessment continues to become both more mature and more complex, most modern risk assessment methodologies look to the early 1980's work of Kaplan for their foundational principles.[1)] A number of important concepts are set out in this body of work, but its central principle is that risk is the combined consideration of both the likelihood of an unfavorable event taking place and the expected consequence should it actually happen. Expansions and modifications to this principle have been proposed; but all of these point back to the joint consideration of likelihood and consequence, with the resultant "risk" typically not reduced to a simple multiplication of these two aspects.

While this principle appeared in the literature more than thirty-five years ago, the operational conduct of spacecraft conjunction assessment (CA) risk analysis almost never incorporates any explicit consideration of collision consequence at all. When CA was at its beginnings and operating against a much smaller space catalogue, conjunctions serious enough to require remediation were relatively rare; so it was acceptable to treat every serious conjunction event as a potential catastrophe and respond accordingly. However, increases to the space catalogue due to the two large space-debris-producing events of this century (2007 Chinese ASAT test and 2009 Iridium-COSMOS collision) have stressed this operating paradigm; and the increases to the space catalogue expected from the planned 2018 deployment of the US Air Force's S-Band Fence debris radar, which could increase the size of the space catalogue by a factor of five or more, adds an even stronger incentive to reconsider this static treatment of collision consequence. A number of modifications to the CA process will probably be required in order to operate smoothly with the much larger number of conjunctions expected with the S-Band-enhanced catalogue, and a durable understanding of collision consequence can help to separate truly high-risk conjunctions from those that, while having a similar likelihood of occurrence, would not produce nearly the same magnitude and quantity of unfavorable effects should a collision occur. In an era in which it is likely no longer to be possible to take remediation action for all serious conjunctions, any ability to make a distinction of severity among a set of likely collisions will be extremely helpful to the risk assessment enterprise.

2. Aspects of Collision Consequence

Historically, collision consequence has been viewed solely in terms of potential effect on the protected asset; and considered from only this perspective, there is no additional analysis required to further understand the implications. While certain collisions might constitute "glancing blows" that leave the protected satellite intact or, for example, merely damage a small portion of a solar array and thus leave the satellite functioning, it would be practically impossible predictively to determine that a particular conjunction would result in a collision of this type. Even if the secondary object is small and light enough to present a relatively benign fragmentation threat, one could not conclude in advance, given the satellite state uncertainties typically encountered in CA, that the secondary would not collide with a critical component on the primary satellite. One can thus see how an asset-centric view of CA could lead to a static understanding of collision consequence such as that employed internationally today.

An accompanying aspect of space protection, however, is preservation of the space environment—protecting it from debris pollution that would greatly complicate satellite operations and in some regimes perhaps make it impossible. There are satellite missions that are extremely well served by particular orbits and rather difficult to perform from others; if these orbits became essentially unusable due to debris pollution, significant additional cost and risk could be brought to satellite operations. Furthermore, increasing debris density risks accelerating the Kessler Syndrome, a condition in which debris density increases to the point that debris production through collisions becomes a self-sustaining and ever-increasing phenomenon, even if another satellite were never launched.[2] All space-faring nations should be deeply concerned about the potential to render important orbit regimes essentially useless by allowing space debris to accumulate to critical levels through inadequate conjunction mitigation and debris production control. When this aspect of the problem is considered, collision consequence assumes a substantially enhanced role in CA risk assessment.

The present paper treats the subject of satellite collision consequence in two parts. First, it examines and proposes methodologies to estimate the amount of debris production that is likely to result from a satellite collision and considers how to incorporate such information into a risk assessment paradigm. Second, it addresses the issue of debris pollution of canonical orbit types and how one might include this consideration in risk assessment in a straightforward way. Finally, it gives a condensed presentation of this work-in-progress risk assessment methodology to consider consequence along with the likelihood of collision, with the latter being well represented by the probability of collision and its proposed variants.

3. Debris Production from Collisions: Theory

The NASA Orbital Debris Program Office (ODPO), located at Johnson Space Center, has been studying the problem of collision- and explosion-spawned space debris for several decades. Based on studies of the results of known satellite collisions and of staged hyperkinetic collisions in a vacuum chamber between mock-up satellites and debris objects, relationships that allow estimation of the number of debris pieces (and other interesting support information, such as area-to-mass ratio distributions) from such events have been developed. These relationships are part of the ODPO's EVOLVE 4 satellite break-up model[3] and are described in summary here.

The basic categorization to be made when evaluating a potential collision for debris-producing potential is whether the collision would be "catastrophic," in which both satellites become completely fragmented; or "non-catastrophic," in which the lighter satellite becomes fragmented but the heavier satellite is merely cratered and thus emerges intact. The governing relationship here is the ratio between the relative kinetic energy of the lighter object to the mass of the heavier object:

$$\frac{mV_{rel}^2}{2M} > 40{,}000\,, \qquad (1)$$

in which m and M are the masses of the lighter and heavier satellites (in kg), respectively; and V_{rel} is the relative velocity of the two colliding objects (in m/s). Analysis of experimental data has determined that if this quantity exceeds 40,000 joules per kg, then the collision will be catastrophic.

Once the catastrophic/non-catastrophic categorization has been established for the collision, a second relationship can be applied in order to determine the expected number of resultant pieces:

$$N(L_c) = 0.1(\mathrm{P})^{0.75} L_c^{-1.71} \quad , \qquad (2)$$

in which L_c is the characteristic length above which one wishes to compute the number of debris objects and P is a momentum term of sorts for the collision: if the collision is non-catastrophic, it is given as the product of the mass of the lighter satellites (in kg) and the relative velocity (in km/s); if the collision is catastrophic, it is the sum of the masses of the heavier and lighter satellites (m + M).

4. Debris Production from Collisions: Practice

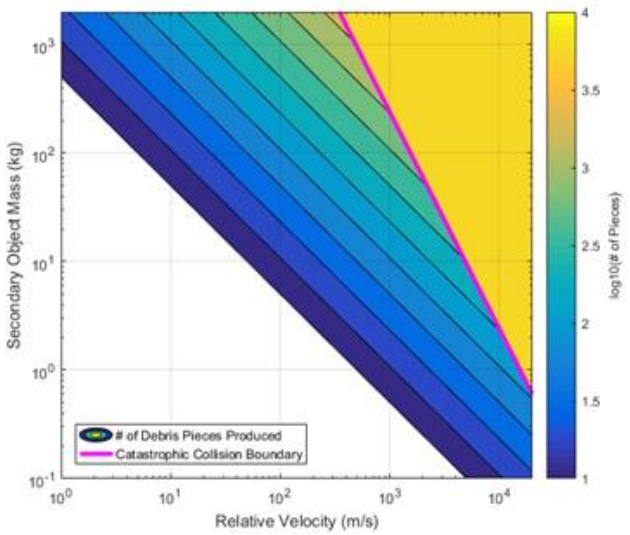
The equation set given in the previous section is straightforward enough to evaluate if, in fact, all of the needed terms are available. Of the four required inputs, three are easy to assemble: the mass of the heavier object, presumed for all intents and purposes to be the protected asset, is known and often known very precisely; the collision velocity is an easy and straightforward calculation, and the desired piece size threshold (L_c) is merely an input. The mass of the lighter object, which is almost always the conjunction secondary, is generally not known and therefore must be estimated; the available estimation techniques are not particularly precise. However, the achievable precision can be considered adequate to make certain claims about collision consequence that can inform the risk assessment process. The following multi-part argument will establish why this is believed to be so.

4.1. Debris-Production Relationship Profiling

In order to understand the level of precision needed for the inputs to these relationships (*i.e.*, Eqs. 1 and 2), it is first helpful to profile the relationships themselves and the key input parameters that are known. Eqs. (1) and (2) are used in nested fashion, namely that one must first characterize the collision as either catastrophic or non-catastrophic and then apply different inputs to the second relation depending on this characterization. Such an approach has the propensity to create discontinuities in the function output, so to investigate this possibility the function pair was profiled by setting the mass of the primary satellite (M) to 3000 km and allowing the collision velocity to vary from 1 to 20,000 m/s and the secondary object mass (m) to vary from 0.1 to 3000 kg. The results are shown below in Fig. 1:

Fig. 1. Collision Debris Production as a Function of Secondary Mass and Relative Velocity

The results are both interesting and intuitive once the forms of

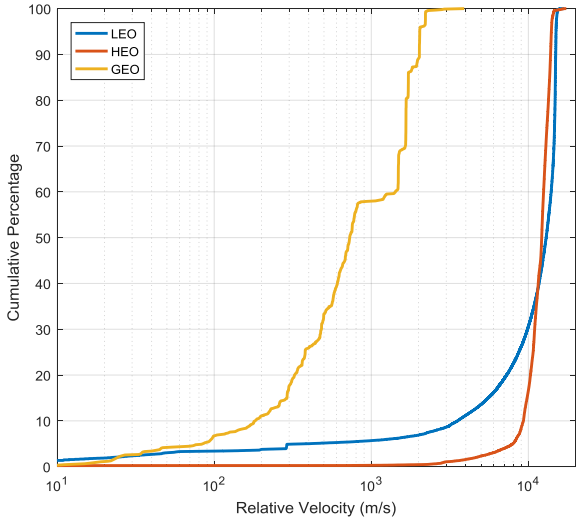


the two expressions are examined. When the two satellites' masses are similar (in this case, two large objects), the number of pieces produced in the non-catastrophic case is larger because although only the lighter satellite fragments, it is a heavy enough satellite that a fair number of debris pieces are produced from its fragmentation; so for the heavier secondaries one sees more of a continuum of piece count values all the way to the catastrophic collision boundary (shown in pink on the contour plot). For lighter secondary objects, there is relatively little increase in the number of pieces before the catastrophic collision boundary is reached; for a secondary mass of 1kg, for example, a collision to the left side of the catastrophic boundary produces only ~100 pieces, whereas a very small increase in velocity pushes one to the right of this boundary and produces a collision with several thousand pieces. Finally, some secondary masses are so light that even at relative velocities of 20,000 m/s they do not produce a catastrophic collision at all and never engender a large number of resultant pieces.

Since conjunction velocity is easily available for past conjunctions, it is helpful to profile this parameter by orbit regime to see which parts of the graph in Fig. 1 will be most heavily frequented. Figure 2 below gives cumulative distribution function (CDF) plots by primary object orbit regime type (LEO is for low orbits with a period less than 225 minutes; HEO is for longer-period orbits with an eccentricity > 0.25, and GEO is for geosynchronous orbits) for the ~1.5M conjunctions contained in the CARA database.

Fig. 2. CDF Plots of Conjunction Relative Velocity, by Orbit Regime

While nearly all HEO conjunctions have relative velocities pushing 10,000 m/s, LEO conjunctions have at least a substantial minority notably below this (~20% less than 7,000



m/s), and GEO conjunctions are considerably slower—perhaps as many as 40% that could not for any mass ratio become catastrophic (based on the profiling results given in Fig. 1). This spread in relative velocities indicates that it is reasonable to expect representation of both high- and low-debris-producing conjunctions, but that even with imprecise estimates of the secondary mass value many conjunctions will remain either high- or low-production. Such a result is encouraging in that it suggests that segregation of conjunctions by the amount of debris produced is in fact possible, and it thus motivates the next state of the analysis.

4.2. Estimating Mass of Debris Objects: Theory

If a conjunction's secondary object is an intact payload or a rocket body, it may be possible to obtain its mass directly, or at least make reasoned guesses, from published dimensions or other data. For space debris objects, however, there is no such *a priori* information; and given that some 80% of conjunction events have a debris object as the secondary, if a method of estimating debris object mass cannot be assembled, then the entire enterprise of using the EVOLVE 4 relations to estimate debris production will not be viable. The methods to be laid out in the following discussion will of their nature be imprecise, but the ultimate issue will be whether even largely imprecise estimates can still bring significant value to conjunction risk assessment.

The modeling of non-conservative forces that act on satellites, usually expressed in terms of atmospheric drag and solar radiation pressure acceleration, implicitly includes solutions for an object's mass. The present investigation will confine itself to examining the atmospheric drag solution to obtain a mass estimate, but the same sort of procedure could be applied to a solar radiation

pressure solution as well; and in fact this latter approach would be preferable for many conjunctions for HEO and GEO primaries. The expression for satellite drag acceleration is given by

$$\ddot{r} = -\frac{1}{2} C_D \frac{A}{M} \rho v_r^2 e_v , \qquad (3)$$

in which *r*-double-dot is the anti-velocity acceleration, C_D is the drag coefficient (dimensionless), *A* is the spacecraft frontal area (normal to the velocity vector), *M* is the spacecraft mass, ρ is the atmospheric density, v_r is the magnitude of the velocity relative to the atmosphere, and e_v is the unit vector in the direction of the spacecraft velocity.[4] The collection C_D, *A*, and *M* cannot be solved for independently as part of the orbit determination (OD), so these three terms are amalgamated into a single term, called the ballistic coefficient, and solved for *ensemble*. For clarity, Equation 4 below restates this relation:

$$B = C_D \frac{A}{M} \quad . \qquad (4)$$

The objective is to determine the satellite mass M, which means that the three remaining terms in the equation must be determined, or at least bounded to some degree. The overall ballistic coefficient *B* is solved for explicitly in the OD, reasonable bounding values on C_D have been established from other studies, and there are methods for estimating the satellite average frontal area from sensor signature data; so in principle *M* can now be determined. The estimation approach for producing a candidate distribution of values for each of these parameters is discussed in the following sub-sections.

4.3. Estimating Ballistic Coefficient PDF

The OD process estimates a mean value for the ballistic coefficient, although sometimes more complex OD processes actually segment the arc and make individualized estimates of local ballistic coefficients and then produce an omnibus estimate over the entire OD interval. The process also produces an estimation variance for this parameter. Generating a population of ballistic coefficient values conforming to these statistical parameters is extremely easy—it is simply a Gaussian distribution with a mean value of *B* and a variance equal to the ballistic coefficient variance.

4.4. Estimating C_D PDF

The issue of determining satellite drag coefficients received sustained study at the beginning of the space age[5,6] and some lower-level research thereafter, to be picked up again in the last decade.[7,8] As remarked earlier, in general the ballistic coefficient was solved for as an ensemble parameter; and as this approach was acceptable for general space surveillance applications (and indeed the only real approach for space debris), less attention was paid to the calculation of the C_D value itself. For satellite payloads, there is often an attempt to generate a higher-fidelity atmospheric drag model that involves a model-based calculation of the satellite's ensemble C_D, based on laboratory measurements; but the in situ C_D often differs by quite a bit from the laboratory calculation, especially in the upper atmosphere, where the gas mixtures, densities, and dynamics differ from the better-studied lower atmosphere and are not always well understood.

The complete absorption of gas particles coming in contact with a satellite's frontal area, were that to happen, would produce an atmospheric interaction with a C_D of 2; because there is particle reflection and re-emittance, the actual C_D is larger than this limiting figure. For snub, squat objects that have aspect ratios close to unity, this represents most of the story. For distended objects with large aspect ratios that maintain the longer dimension parallel to the velocity vector, thermal motion of gas particles causes additional broadside momentum exchange, thus pushing the CD to even higher values. Based on the studies to date,[7,9,10] snub objects tend to possess CD values of 2.2 to 2.8 depending on object specifics and atmospheric temperature; stable, distended objects in the proper orientation can manifest values of 4 and higher. Trying to assign CD values to debris for which little is known about object shape is difficult and is a suitable subject for additional study; but for the present application, a uniform distribution of CD values ranging from 2.1 to 3.0 is employed. While some geometries can manifest higher values, the unstabilized nature of debris should produce average CD values in this range, or at least close to it. The final debris count estimation results are relatively insensitive to this value, as will be discussed when these results are presented.

4.5. Estimating Satellite Frontal Area PDF

For intact spacecraft and rocket bodies with published shapes and dimensions, one can attempt to generate an estimate of an average frontal area from this information, although the reliability of published satellite design details is often uncertain. In any case, an estimation procedure will be needed for debris objects, for which there is no available dimensional information. Fortunately, methods exist for estimating this parameter from satellite signature data taken from sensors; and because the present interest is LEO objects, the signature datum on which to focus is the radar cross-section (RCS) of the satellite—a quantity that is correlated with satellite size/area and that is measured along with the positional information during radar tracking.

Even though RCS has the units of area, only under certain circumstances can its value be roughly equated to satellite cross-sectional area. The blue line in Fig. 3 below shows normalized RCS values for a perfectly-conducting sphere, the only shape for which an analytic RCS solution exists.[11] While perhaps the simplest shape to model, it has its own special complexities. The x-axis gives a normalized version of sphere size (ratio of sphere circumference to radar wavelength), and the y-axis a normalized value of RCS return (ratio of RCS to sphere cross-sectional area). The oscillatory behavior in the middle part of the graph is due to radar waves "creeping" around the sphere and thus, depending on the ratio of wavelength to sphere size, causing constructive or destructive interference to the radar backscatter return. One observes that, eventually, the graph converges to unity at a value of $2\pi r/\lambda$ equal to about 20; this is the point at which at least a rough equivalence between RCS and object cross-sectional area can be supposed. However, this convergence is reached only for objects that are much larger than the typical debris secondary object encountered in CA. At S-Band, which is the frequency at which the large debris tracking radar currently being built by the USAF will operate, one reaches the beginning of the convergence region at sphere diameters of 0.86 to 1.7 m ($2\pi r/\lambda$ values of 10 to 20), and these values are only larger for radars operating at lower frequencies. The majority of the debris objects that constitute secondaries are smaller than 30 cm and thus fall well below the

object sizes for which a RCS / physical area equivalence could be postulated.

Fig. 3. Normalized RCS vs Normalized Object Size, for a Perfectly-Conducting Sphere and the NASA Size Estimation Model

An additional complication is that RCS response depends on the shape of the object tracked; so if the object is small enough to lie outside of the convergent situation described above, and the great majority of LEO debris objects would be, the shape of the object has an effect on the response intensity and thus estimates of the resultant size. Not only does the shape itself affect the return strength in an overall sense, but the particular face that the irregular object presents to the radar at the time of tracking influences it as well; this is why fluctuation models for RCS response to describe an expected PDF of RCS return histories, such as the Swerling models, have been developed.[12] Handbooks of RCS response have been assembled for a number of different canonical shapes;[13] and the number of different response types, nearly all of which are empirical and not capturable by any theory-based analytical expression, can easily overwhelm the researcher and make any sort of ability to link RCS results to object shapes and sizes seem almost impossible.

Recognizing this difficulty when performing their debris surveys, some years ago the ODPO developed a size estimation model (SEM) that attempted to bring some regularity to this process for a special class of objects, namely small debris smaller than 20 cm.[14] To simulate on-orbit debris production, a satellite was fragmented in a vacuum chamber with a hyperkinetic impact and the expected trackable fragmentation pieces collected. Each of these pieces was assigned a "characteristic dimension" through a somewhat complicated process of beginning with the longest segment inscribable in the object, then the second largest such segment that is also orthogonal to the first, then the resultant third orthogonal segment, and finally averaging the three values. Next, each object was placed in an anechoic chamber and illuminated in all possible orientations with a radar that operated through a large range of frequencies, with RCS values recorded. Finally, applying a radar theory framework, a dimensionless relationship was established between characteristic dimension (normalized by radar wavelength) and RCS (normalized by the square of the radar wavelength). For objects extremely large and small compared to the radar wavelength, the SEM overlaps with the same response as is seen for the sphere, conforming to theory; for the transitional region between, the SEM results show a non-oscillatory behavior that is somewhat larger than that for the sphere. Figure 3 shows the SEM response on the same graph as the ideal sphere behavior.

Using this relation, one now has a method to establish a unique mapping between a RCS value and a characteristic dimension, the latter of which could be used to calculate an object projected area and thus complete all of the inputs needed for the estimation of object mass. Before progressing too far with this, however, one must remain mindful of which uses of this relationship are in accord with its development intent and which would be considered "off-label." The usual and expected application of the SEM is to transform an entire distribution of RCS data collected in debris surveys into an accompanying distribution of object size data. The expectation is not that this relationship can give a definitive size value for a particular object; instead, it is believed that it can give a representative distribution of sizes given a distribution of RCS values. Additionally, since the fragmentation pieces examined in assembling this model were all smaller than 20 cm, the fidelity of the relationship when applied to objects larger than this size is not known. Finally, any wide application of the model presumes a similarity in material composition between the satellite fragments used for the model's development and those that constitute the broader space debris population. So care must be exercised in how the model is applied, and some sort of evaluation activity should be pursued to certify the basic rectitude of the approach.

Such evaluation is difficult because there is almost never *a priori* size information on space debris objects. However, there is one class of debris objects that does have quasi-independent size data: RORSAT coolant spheres. The RORSAT satellite group were nuclear powered and contained a cooling assembly employing a sodium-potassium liquid coolant; after satellite passivation, the cooling assembly had a propensity to leak this liquid coolant, which because of its high surface tension collects into spheres with diameters in the 5-6 cm range. A detailed examination of twenty-four of these satellites using extremely high-fidelity tracking radars was able to confirm their spherical nature through radar polarization studies and establish their size to within two-tenths of a centimeter or better.[15] Employing the above procedure to estimate the size of these objects (namely the NASA SEM with routine JSpOC RCS data) and using the known density of NaK to estimate satellite masses, one can compare the results obtained from the definitive calculations to those obtained with the NASA SEM procedure. Residual CDFs for both results sets are given in Fig. 4 below. In both cases, the differences are calculated as the base 10 logarithm of the ratio of the SEM to the definitive calculation, thus in orders of magnitude (OoM).

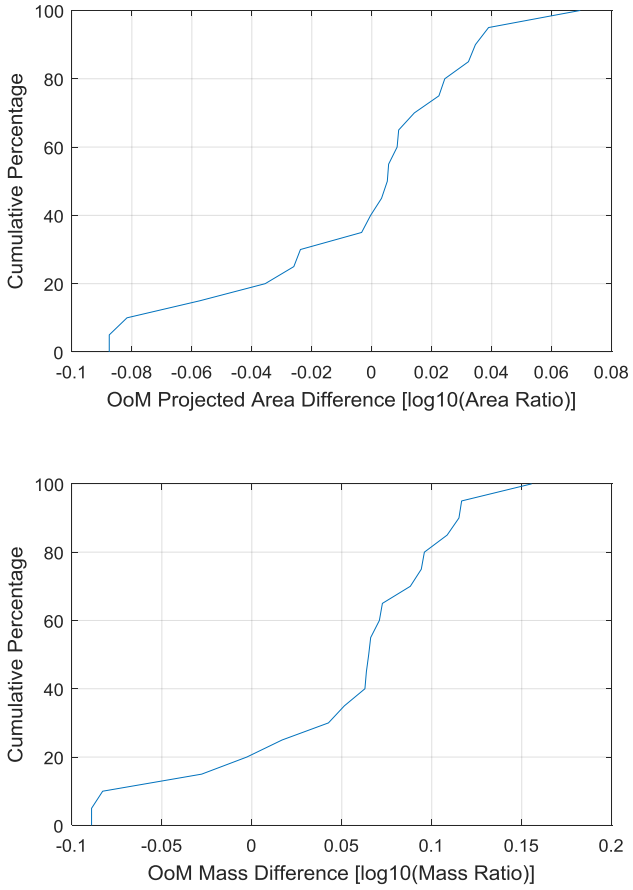


Fig. 4. CDF Plots of Estimation Residuals for RORSAT Coolant Sphere Characteristics

These residual sets are quite encouraging. The overall error in size determination is very small; and when the mass itself is estimated from the ballistic coefficient equation and compared to actual mass calculations (from the established size data and NaK density), the difference stays below 0.15 of an order of magnitude, which is very good behavior indeed. There is a positive bias to the residuals, and this is likely to be an issue that will abide with any RCS-based analysis, for the following reason. Changes in viewing geometry (not an issue with spheres but a strong contributor in the general case), radar operating conditions, atmospheric conditions, and specular response will act to alter the signal-to-noise ratio (SNR) of the radar return, either to increase or to decrease it depending on the particular circumstances; and changes to the SNR (keeping all other aspects of the tracking encounter the same) map directly into the RCS value. When the SNR is increased, the object is even more likely to be tracked, and the RCS value is calculated and recorded; when the SNR is decreased, it may become low enough that track quality criteria are not met, and the particular track is thus abandoned (and any resultant RCS calculation with it). It is for this reason that RCS histories tend to ride high rather than low—there is a left-censoring of the smaller values; and if used uncompensated, quantities that derive from RCS values (size and area estimates) will also tend to be somewhat overstated.

At present there is no rigorous, or even general, error analysis or statement to apply when using the NASA SEM to estimate sizes of actual satellites from RCS values. In order to determine the viability of the concept, therefore, a broad error range will be assigned to the satellite frontal area estimates derived from this method. Because any error in size will be exponentially related to the error in satellite frontal area, it is more straightforward simply to apply the broad error range to the area calculation. The very generous error range proposed for the present analysis is a uniform distribution from an order of magnitude below the area estimate (or one square centimeter, whichever is larger) to an order of magnitude above the area estimate. In order to apply the uniform distribution of area over a region that is logarithmically defined, when performing Monte Carlo sampling half of the samples are drawn from a uniform distribution explicitly defined from the lower boundary to the estimated value and the other half from a separately-defined uniform distribution defined from the estimated value to the upper boundary, booth in linear space. This forces an equal number of samples to come from each side of the estimated value. One could argue that the samples should be positive-biased in order to align with the expected response (as described in the previous paragraph), but this is achieved implicitly by the presumption of a positive bias in the estimated value.

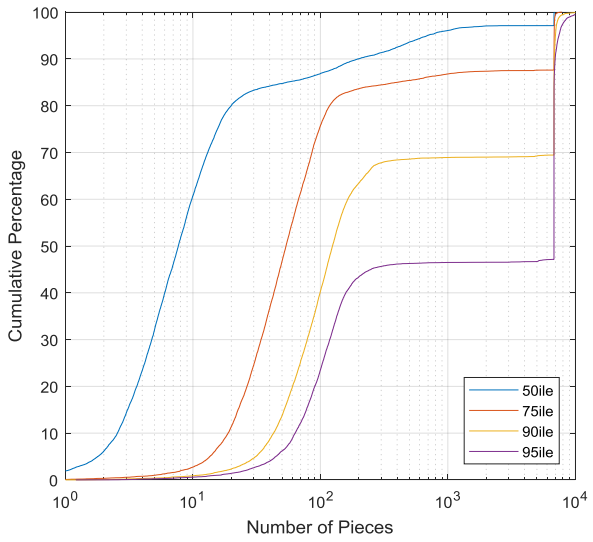
4.5. Procedure for Mass Estimation and Calculating Debris Production

Now that a methodology, admittedly imprecise, has been proposed for estimating the mass and thus expected amount of debris production from satellite collisions, it is time to profile the results against a database of historical conjunctions to determine whether even with these very large error bounds meaningful differences can be established between conjunctions in terms of the amount of expected debris generated. For the profiling experiment, the CARA database of conjunctions spanning from January to June 2016 was used; this yielded slightly more than 14,000 unique conjunction events for which the secondary was a debris object and for which an RCS value for this secondary is available. For each such event, a representative estimate for the two satellite states was chosen (usually the one that produced the maximum Pc, although this was an arbitrary and not particularly important choice) to provide the collision velocity, ballistic coefficient and variance, and RCS value for the encounter. One hundred thousand samples of the ballistic coefficient (generated using the mean B term and variance from the OD), drag coefficient (using the uniform distribution between 2.1 and 3.0), and frontal area (generated with the wide uniform distribution about the estimated value described above) were generated and, through the relationship given in Equation 4, used to create a PDF for the resulting mass of the secondary object. This PDF was used in conjunction with Equations 1 and 2 to produce a PDF of expected collision debris piece counts greater than 5 cm; this PDF was then characterized by percentile points (50, 75, 90, and 95th percentiles). The results of the profiling for all of the 14,000 cases are summarized by CDF in Fig. 5 below:

Fig. 5. CDF s for Conjunction Piece Counts of Historical Conjunctions,

Segregated by Percentile Band

This results set is also encouraging in that, at the confidence levels that will probably be desired by CA practitioners, a reasonable amount of discrimination is exhibited among the different events with regard to debris production. If one wishes to operate at the highest confidence level (95th percent confidence here), one can say that about half of the events will generate less than 200 pieces of debris (non-catastrophic



collision with relatively light secondary object) and the other half will produce a catastrophic collision with several thousand pieces of debris. While a few hundred pieces of debris is not negligible, it is certainly far less polluting and worrisome than debris piece-counts an order of magnitude larger. The outcome is shaped conveniently as a threshold issue: either the collision remains non-catastrophic and produces a relatively small number of pieces, or it becomes catastrophic and generates a large amount of debris. If the 95th percent confidence interval is the one followed, an operational statement corresponding to this outcome could be the following: "one out of twenty times an event such as this will produce a very large amount of debris and thus must have its probability of collision remediated to a lower level."

This approach is viable only to the degree that it is believed that the errors in estimating the projected area lie within an order of magnitude of the estimated value. Based on the RORSAT results, this seems to be a reasonable initial postulation; but it is certainly desirable to bring some additional test data to the construct, perhaps tracking data from microsatellites for which published dimensional data are available. Such satellites do not assume the same shapes of typical debris objects (whereas a spheroid is one of the four canonical shapes that debris objects exhibit,[16] so one must exercise care in using intact spacecraft with all of their geometric eccentricities to represent space debris; but it is an important area of future work on this construct to establish that the one order-of-magnitude error bounds on the projected area are in fact reasonable. Such boundaries certainly seem quite generous, but this belief would benefit from additional analytical substantiation. One sensitivity analysis was run using a C_D span from 2.1 to 4 rather than 2.1 to 3, with the result that the "plateaued" levels of Fig. 5 dropped by about eight percentage points; in short, the graph's morphology was essentially unchanged, showing that errors in C_D determination are easily absorbed by the construct.

5. Pc Threshold Modifications for the Low-Debris Case

The present operational paradigm among most CA risk assessment practitioners is to treat every conjunction as a potentially catastrophic collision, so the expected adjustment for potential collisions that appear unlikely to produce large numbers of debris objects would be to make the Pc threshold at which remediation is pursued to be more permissive. The decision of how much more permissive to render the threshold will be subjective, as there is no precisely-defined relationship governing the apportionment of risk between protecting a payload and protecting its orbital regime. However, one can proceed by analogy to other operational situations that presently receive a decrement in remediation threshold for other reasons. Payloads that face impediments to remediation, such as those that use electric propulsion and therefore are much more limited in the remediation actions that they can effect, are often given up to a one order-of-magnitude offset in remediation threshold, to wit: if the usual remediation threshold were when the Pc exceeds 1E-04, such satellites would be expected to perform remediation actions only for situations in which the Pc exceeds 1E-03. What is thus proposed here is a 0.5 to 1 OoM leniency offset in the Pc remediation threshold for those situations in which the collision is expected to remain non-catastrophic, with the exact value being dictated by the particular sensibilities of the CA entity and the owner/operator of the protected asset.

6. Orbital Corridor Population

It seems conceptually straightforward to postulate that debris-producing events in heavily-populated orbital corridors are more worrisome than those taking place in those that are only lightly populated; after all, the number of protected assets, and therefore the number of expected serious conjunction events, would be expected to be larger in heavily-used orbital regimes. It also would seem fairly straightforward to assemble density maps of the orbital population and define high-density areas for which conjunctions should be remediated more aggressively.

Once one begins to work the problem in more detail, however, additional difficulties arise rather rapidly. For example, consider the sun-synchronous orbit, a mainstay for earth-observing satellites because the proper alignment of inclination and altitude can control the nodal procession to one degree per day and thus preserve the same mean local time at each equatorial crossing. While there are some instantiations of the sun-synchronous orbit that are more popular than others (for example, there are a number of satellites that have chosen a sun-synchronous orbit with an altitude slightly above 700 km), in fact there are a large number that have selected quite different altitudes and inclinations. Even if the more populated instantiations of this particular orbit type were identified and selected for special protection, this only addresses the satellites

immediately threatened by a collision in that regime; debris-producing events at higher altitudes that might seem rather remote from the protected area can push debris into that protected area rather easily, and debris resident at a higher altitude can "rain down" on the protected area as the debris decays naturally. As an example, the two largest space-debris-producing events, the 2007 Fengyun-1c ASAT test and the 2009 Iridium-COSMOS collision, took place at orbital altitudes of 865 and 790 km, respectively; but more than 50% of the collision events against the A-Train satellites (sun-synchronous orbit at 705 km) are caused by debris from these two events. It would have been difficult to call orbital regimes 100km or more away in altitude part of a protected zone about the A-train region, but nonetheless collisions that took place in that more distant area increased the threat profile substantially in the A-train region. A similar conclusion would be expected for other special orbits, such as the Molniya elliptical orbit (which maintains a fixed argument of perigee due to the J2 gravitational effect).

One notable exception is the geosynchronous orbit. While improvements in geosynchronous satellite capabilities have allowed these satellites to sustain a larger inclination variation than in previous times, even so daily penetrations of the equatorial plane remain; and many geosynchronous satellites do not take these additional liberties in inclination and require near-constant planar presence. Geosynchronous debris-producing events, no matter their specifics, will all leave at least some debris in the geosynchronous plane. Furthermore, depending on the debris objects' initial velocities, some could circle the geosynchronous belt for years before they become captured by one of the two geosynchronous libration points; and even then they can librate some distance from the point before their relative motion becomes sufficiently dampened to prevent their remaining a threat to other geosynchronous satellites. Any debris created in and not ejected out of the geosynchronous orbit will, therefore, constitute a long-term threat to a good number of the active geosynchronous objects. For this reason, it is recommended that all conjunctions in this orbit regime be remediated to the same level as those determined to be catastrophic, even though they might actually produce a modest amount of debris; the persistence of this debris and its easy access to many of the other geosynchronous objects makes such additional caution prudent..

6. Conclusion and Future Work

While the incorporation of consequence into CA risk assessment is very much a work in progress, efforts to date are presently recommending a construct that can be summarized by the following matrix, in which the boxes contain the Pc value at which remediation is recommended:

	LEO/HEO Orbits	GEO Orbits
Catastrophic Collision	X	X
Non-Catastrophic Collision	X + (0.5 – 1) OoM	X

As discussed previously, small-debris-producing collisions can be afforded perhaps half an order-of-magnitude relaxation in the remediation Pc. In the LEO and HEO orbit regimes, it is difficult in the absence of extensive studies documenting the full evolution of produced debris to determine the full effect of collision debris on any particular protected regime; so it is best to treat any collision there as uniformly potentially damaging to any other LEO/HEO area. For the GEO regime, an abatement for non-catastrophic collisions is not recommended due to the persistent threat any debris produced from a GEO collision will present to many, and perhaps all, protected GEO payloads.

Future work will focus on further testing of the area-estimation methodology, at the least to generate better error bounds than the one OoM uniform distribution suggested presently. Additionally, the development and incorporation of a debris evolution model into the risk-assessment process would help quantify more precisely the threat that a particular conjunction would present, both immediately and over time, to a set of protected satellites and thus allow a more informed consideration of whether the remediation threshold in such a situation should be adjusted.

Acknowledgments

The authors would like to thank fellow Conjunction Assessment Technical Advisory Council (CATAC) members Bryan Corley, Chikara Harada, William Holworth, T.S. Kelso, Nakamura Shinichi, and Roger Thompson for their support and counsel in developing the ideas and constructs presented in this paper.

References

1) Kaplan, S. and Garrick, B.: "On the Quantitative Definition of Risk." *Risk Analysis*, Vol. 1 No. 1 (1981), pp. 11-27.
2) Kessler, D.J. and Cour-Palais, B.C.: "Collision Frequency of Artificial Satellites: The Creation of a Debris Belt." *Journal of Geophysical Research* 83 (1978), pp. 2637–2646.
3) Johnson, N.L., Krisko, P.H., Liou, J.-C., and Anz-Meador, P.D.: "NASA's New Breakup Model of EVOLVE 4.0." *Advances in Space Research*, Vol. 28 No. 9 (2001), pp. 1377-1384.
4) Montenbruck, O. and Gill, E:. *Satellite Orbits: Models, Methods, and Applications.* Berlin: Springer Verlag, 2005.
5) Jacchia, L.G.: "Variations in the Earth's Upper Atmosphere as Revealed by Satellite Drag." *Reviews of Modern Physics* Vol. 34 No. 4 (1964), pp. 973-991.
6) Cook, G.E.: "Satellite Drag Coefficients." *Planetary and Space Science*, Vol. 13, No. 10 (1965), pp. 929-946.
7) Pilinski, M.D., Argrow, B.M., and Palo, S.E.: "Drag Coefficients of Satellites with Concave Geometries: Comparing Models and Observations." *Journal of Spacecraft and Rockets* Vol. 48, No. 2 (March April 2011), pp. 312-325.
8) Mehta, P.M. *et al.* "Modeling Satellite Drag Coefficients with Response Surfaces." *Advances in Space Research* 54 (2014), 1590-1607.
9) Moe, M.M., Wallace, S.T., and Moe, K.: "Recommended Drag Coefficients for Aeronomic Satellites." *Geophysical Monograph 87: Upper Atmosphere and Lower Thermosphere* (1995), pp. 349-356.
10) Moe, K., Moe, M.M, and Wallace, S.D. "Improved Satellite Drag

Coefficient Calculations from Orbital Measurements of Energy Accommodation." *Journal of Spacecraft and Rockets* Vol. 35, No. 3 (May-June 1998), pp. 266-272.

11) Richards, M.A., Scheer, J.A., and Holm, W.A.: *Principles of Modern Radar*. Raleigh, NC: Scitech Publishing, Inc. 2010.
12) Swerling, P.: "Probability of Detection for Fluctuating Targets." *IRE Transactions on Information Theory Special Monograph Issue*, IT-6 (April 1960), pp. 269-308.
13) Ruck, G.T., Barrick, D.E., Stuart, W.D. and Krichbaum, C.K.: *Radar Cross-Section Handbook*. Los Altos, CA: Peninsula Publishing, 1970.
14) Barton, D.K. *et al.:* "Final Report of the Haystack Orbital Debris Data Review Panel." NASA JSC Technical Memorandum 4809, February 1998.
15) Rosenberg, F.D.: "Radar Characterization of RORSAT Coolant Spheres and their Potential Use for Calibration and Validation of Debris Tracking Sensors." MIT Lincoln Laboratory Project Report STK-264, 26 NOV 2003.
16) Hejduk, M.D., Cowardin, H.M., and Stansbery, E.G.: "Satellite Material Type and Phase Function Determination in Support of Orbital Debris Size Estimation." 2012 AMOS Technical Conference, Kihei, HI. September 2012.