Consideration of Collision “Consequence” in Satellite Conjunction Assessment and Risk Analysis

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June 9, 2017

Agenda

- **Risk assessment foundational theory**
- **Aspects of collision consequence**
- **Collision debris production basics**
- **Estimating debris production for a particular satellite collision**
- **Proposed conjunction remediation threshold alterations for low-debris collisions**
- **Orbital corridor protection**
- **Summary of initial proposed construct for considering collision consequence within conjunction assessment (CA)**
- **Future work**

Risk Assessment Foundational Theory

- **Risk assessment approaches based on Kaplan construct (1981)**
- **Risk is combination of event likelihood and event consequence**
  - Sometimes treated as product of these two, but this is not always appropriate
- **CA has only partially followed this approach**
  - Large body of work on methods to establish collision likelihood
  - Usually static treatment of collision consequence—all satellite collisions uniformly considered catastrophes of highest order
- **In early days of CA, with relatively few conjunctions, static concept of collision consequence acceptable**
- **In current environment, approach needs re-examination**
  - Number of conjunctions much larger now
  - Deployment of USAF Space Fence radar (September 2018) could increase space catalogue by up to a factor of five
  - Consideration of consequence could reduce conjunction remediation need

Aspects of Collision Consequence

- **Protection of primary asset**
  - Some conjunctions could leave primary asset only crippled but still functional
    - “Glancing blow” or injury/degradation to part of solar array
  - However, with current accuracy levels not possible to predict that a particular conjunction would leave only damage of this type
  - For any collision, should thus presume complete loss of primary asset
- **Protection of orbital corridors and space environment**
  - Many orbital types significantly enable particular mission types
    - *e.g.,* geosynchronous, sun-synchronous, Molniya
  - Debris fields from satellite collisions could permanently ruin these corridors
  - Satellite collisions do have very different debris-producing potential
  - In contended environment, expected debris production can be discriminator
    - If not all serious conjunctions can be remediated, debris production potential is possible input to choosing which receive remediation
- **Can one determine the “debris production potential” of a collision?**
  - NASA Orbital Debris Program Office (ODPO) provides possible methodology

Two Collision Types: Catastrophic and Non-Catastrophic Collisions

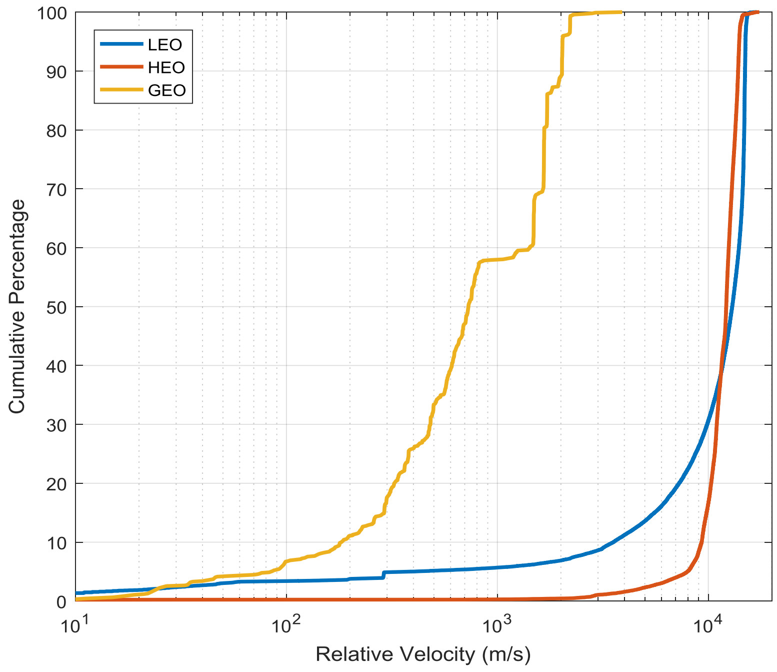
- **In catastrophic collisions, both satellites are completely fragmented**
- **In non-catastrophic collisions, the smaller object is fragmented but the larger one merely cratered**
- **Former situation obviously produces more debris**
- **Undoubtedly there are intermediate cases, but this is the ODPO's basic distinction**
- **ODPO methodology for distinguishing between cases: ratio of relative kinetic energy of smaller object to mass of larger object**
  - Presumed formula: $0.5 * m * Vrel^2 / M$
  - If ratio exceeds 40,000 Joules / kg, then collision is catastrophic

Determining Number of Collision Pieces

- **NASA ODPO EVOLVE 4.0 model contains relationship for number of pieces greater than a certain size generated by a collision**
  - $N(Lc) = 0.1(M)^{0.75}L_c^{-1.71}$
  - Lc is the characteristic length (in meters) above which one is interested in the number of pieces; in a Space Fence era, one might set this to 0.05m
  - M is a momentum component of sorts, and its determination is governed by whether the collision is catastrophic
    - If catastrophic, M is sum of both spacecraft masses (kg)
    - If non-catastrophic, M is mass of smaller object (kg) * collision velocity (km/s)
- **Question: what is dynamic range of results for CA from coupling of catastrophic / non-catastrophic and debris production equations?**
  - *e.g.,* will all results be catastrophic and thus high-debris, rendering approach unhelpful for distinguishing among conjunctions?
  - Profiling activity needed to show viability

Coupled Equation Input Profiling: Satellite Mass and Conjunction Velocity

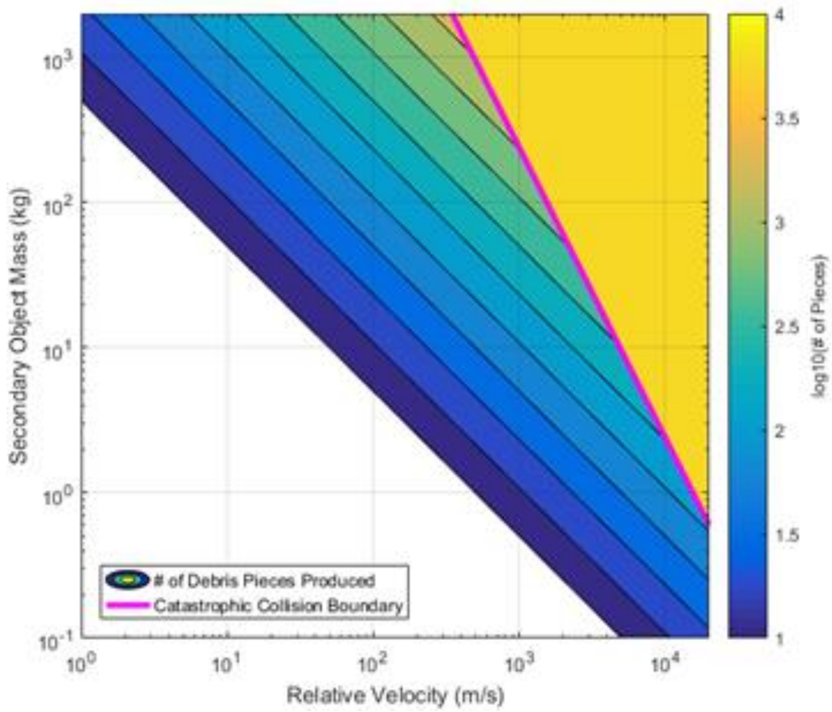
- **Conjunction velocities from NASA CA DB (~1.5M conjunctions) shown at right**
  - For LEO and HEO, great majority exceed 10,000 m/s
  - GEO much slower: 100 to 2000 m/s
- **Masses have large range as well**
  - Primary payload: up to ~3000km or larger
  - Secondary: from 0.01 kg to payload mass
- **Profiling should consider dynamic range of both input types**
  - For this analysis, primary object mass set to 3000 kg



Coupled Equation Input Profiling: Results

- **Catastrophic and non-catastrophic regions distinct**
  - Catastrophic yellow; non-catastrophic layered; magenta line is boundary
- **As mass of lighter satellite approaches that of heavier, more of a continuum in debris production with relative velocity**
  - With lighter secondary, discontinuity increases
- **Even at high collision velocities, non-catastrophic collisions quite possible for light secondaries**
- **In short, construct looks promising as possible severity discriminator**

Primary object mass set to 3000km



Collision Debris Production Determination: Estimating Needed Parameters

- **Conjunction velocity easily obtained from orbital states**
- **Primary object mass known**
- **Secondary object mass must be determined**
  - For intact payloads and rocket bodies, might be able to obtain actual mass value
  - In general (and for debris), mass values will have to be estimated
- **Proposal: estimate mass from ballistic coefficient solution**
  - Ballistic coefficient given by (could also use solar radiation pressure coefficient):

$$B = C_D \frac{A}{M}$$

  - If ballistic coefficient, drag coefficient, and frontal area estimated, then satellite mass (M) can be further estimated from above relation
  - Given imprecisions for many of these parameters, best to define a PDF for each and thus generate an estimated mass PDF
    - Can be further used to generate a debris piece count PDF

Collision Debris Production: Estimating Ballistic Coefficient (B)

$$B = C_D \frac{A}{M}$$

- **Conjunction Data Message (CDM) for particular event gives information about B for primary and secondary objects**
  - Estimate of mean value (B_μ)
  - Estimation variance (B_σ) from covariance matrix
- **Set of random B values easily generated by N(B_μ, B_σ)**

Collision Debris Production: Estimating Drag Coefficient (C_D)

$$B = C_D \frac{A}{M}$$

- **Because ballistic coefficient usually solved for as a single value, relatively less research work directed to C_D**
  - Sustained interest is from atmospheric community, due to attempts to back out atmospheric density values from satellite drag solutions
- **Early work in 1960s, with follow-up in 1990s, established basic principles and rules of thumb**
  - Snub satellites have typical C_D value of 2.2
  - Distended satellites with long dimension along velocity vector have larger C_D, often in range of 3-4
- **Recent interest in topic and better models, but are satellite-specific**
- **For current approach, C_D values generated by U(2.1, 3.0)**
  - Non-stabilized debris unlikely to generate truly large C_D values
  - Supported by Hubble Space Telescope value of 2.8

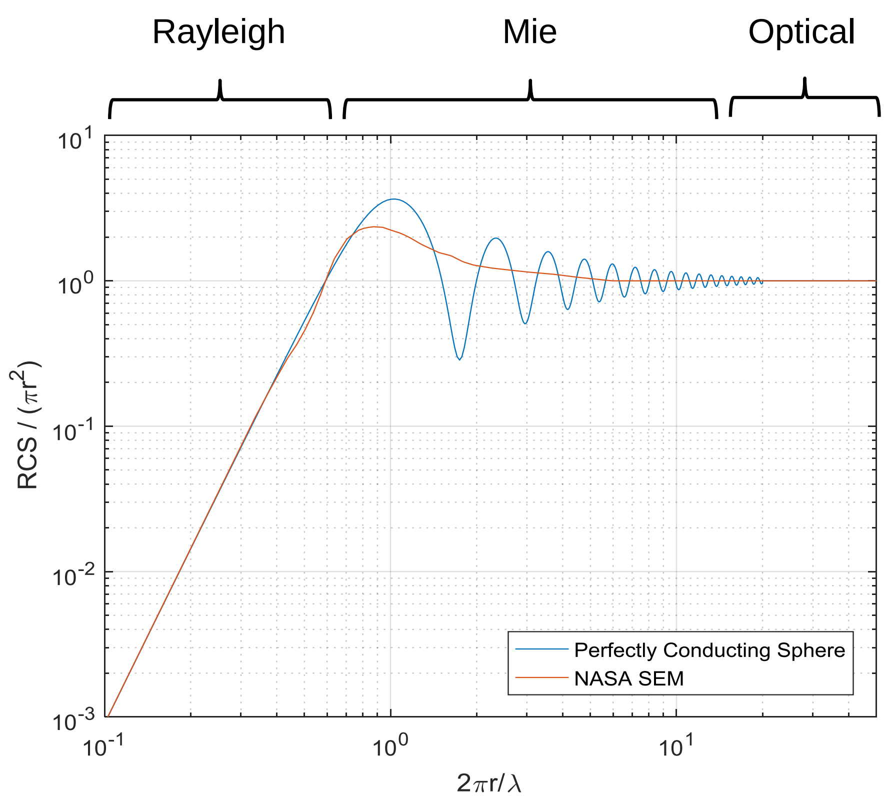
Collision Debris Production: Estimating Satellite Frontal Area (A)

$$B = C_D \frac{A}{M}$$

- **Possible to estimate satellite areas from sensor signature data**
  - Focus on radar cross-section (RCS) as opposed to satellite visual magnitude, since emphasis here is LEO debris
- **RCS has units of area, but only under special circumstances can value be roughly equated to satellite physical area**
- **RCS for sphere illustrates issues with establishing RCS-size relationship (next slide)**
- **ODPO developed Size Estimation Model (SEM) to facilitate mapping**
  - Exploded satellite in vacuum chamber, determined characteristic dimension of each piece, took RCS measurements on each piece, and effected theory-enabled fit of data
  - Intended only for debris smaller than 20cm and to convert entire distributions of RCS to distributions of size, and vice versa
    - Any other use is “off-label”
  - Can be used as starting point for single conversion, with much imprecision

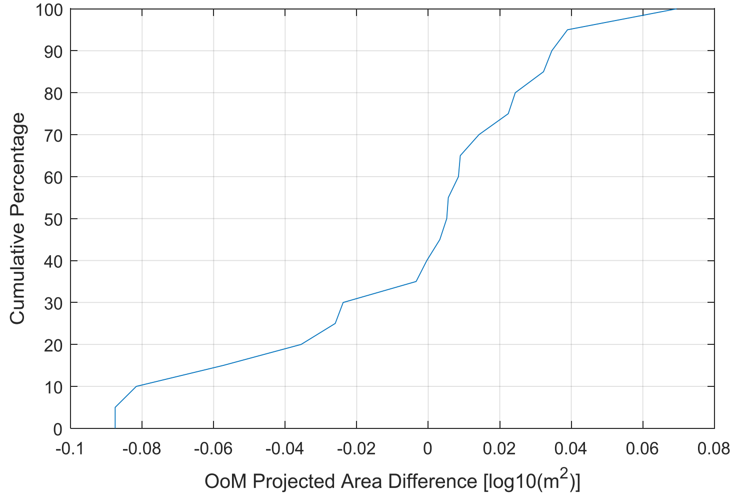
RCS/Size Properties: Conducting Sphere and NASA SEM

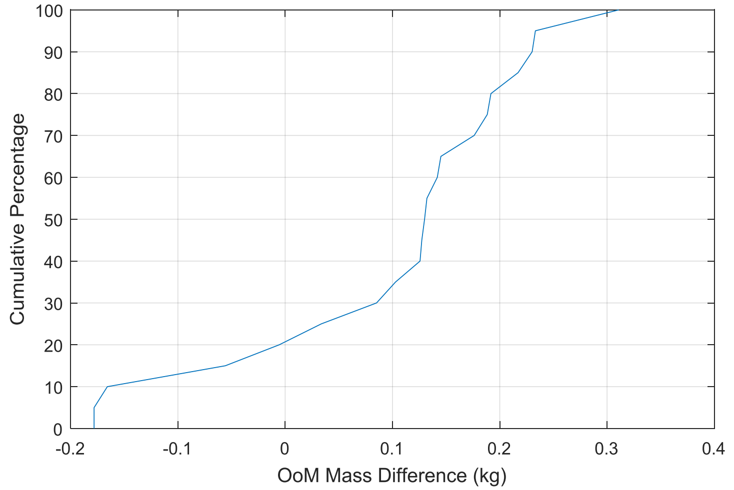
- **Sphere: three regions of response**
  - **Rayleigh**—RCS proportional to r^4
  - **Mie**—transitional region with oscillating behavior (creeping waves)
  - **Optical**—RCS converges to area
    - Unfortunately, at S-Band occurs only for objects greater than 0.86 – 1.7 m; much larger than most debris
- **NASA SEM**
  - Within envelope of sphere response
  - Imposes unique mapping
  - Not precise for single-object use, but how close is it actually?
    - Difficult to evaluate performance against debris (no ground truth)
    - RORSAT spheres offer one opportunity



Frontal Area and Mass Estimation: RORSAT Coolant Spheres

- **RORSAT satellite coolant**
  - Nuclear-powered sats with NaK coolant
  - Leaked out of dead sats; formed spheres
  - Independent study determined sats spherical and 5-6cm in diameter
  - Only debris set with established dimensions
- **24 had sufficient data for study**
  - B and RCS terms
  - Calculated projected areas from RCS (using SEM) and compared to actual areas
  - Performed mass estimation and compared to "actual" masses (calculated from established sizes and known density)
- **Results at right**
  - Moderate positive bias (typical when working with RCS values), but overall error range quite small





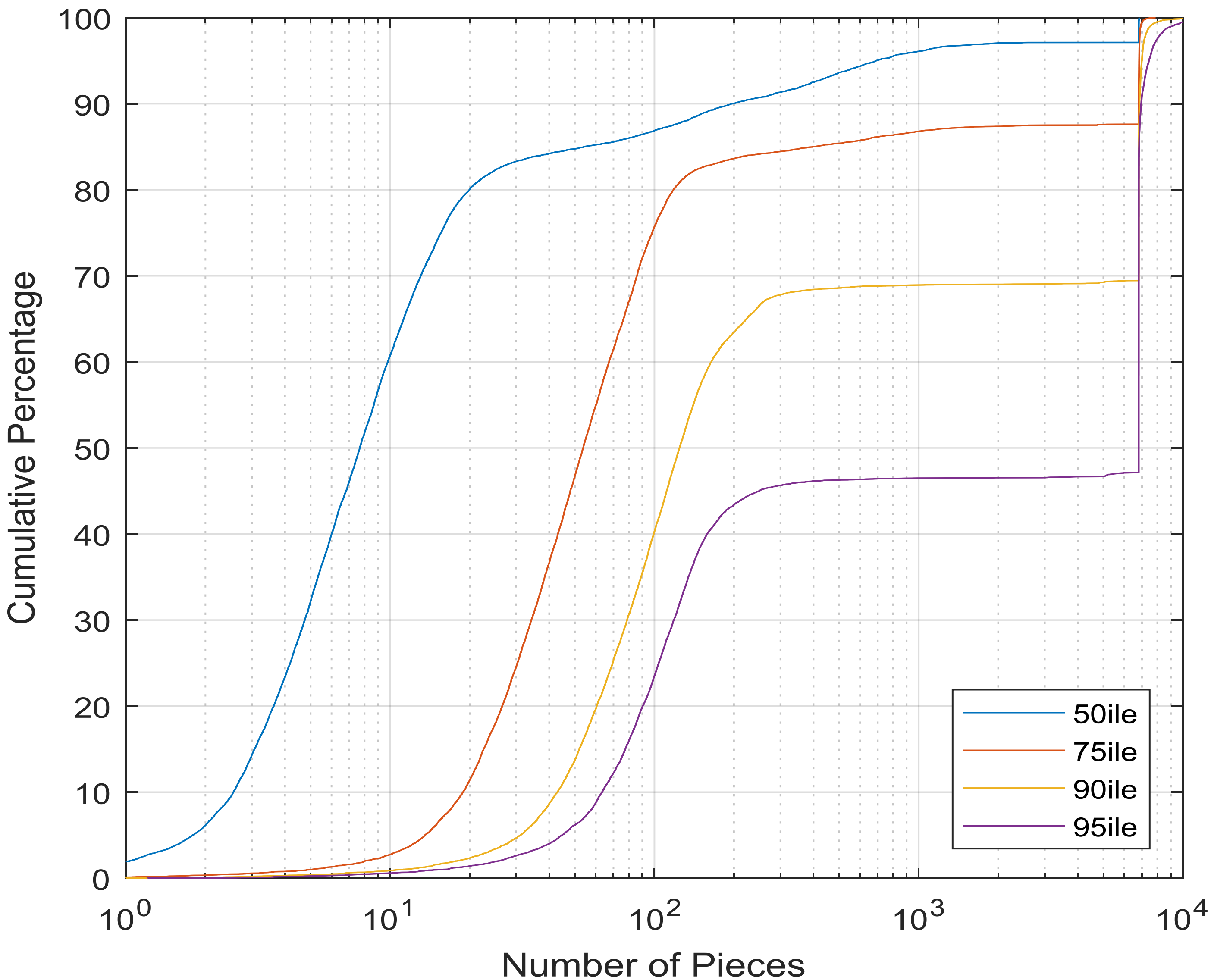
Mass Estimation Procedure: Summary

- **Obtain needed orbital and signature information from latest CDM**
  - B_μ, B_σ, median RCS value
- **Create X samples of each input to ballistic coefficient equation**
  - B from normal distribution defined by B_μ and B_σ
  - C_D from uniform distribution between 2.1 and 3.0
  - A from RCS value fed into SEM, turned into circular area, and used as anchor for uniform distribution +/- one order of magnitude (OoM) from anchor
    - *e.g.,* if anchor is 0.02 m2, samples for A are [U(0.002, 0.02, X/2); U(0.02, 0.2, X/2)]
    - Extremely generous error bounds—presumes SEM only good to +/- 1 OoM
- **Yields X values for secondary object mass**
- **V_{rel} and primary object mass presumed known without error**
- **By using debris production equations, can generate X estimates of amount of debris that collision will produce**
- **Can break down X estimates by percentile points**
  - For most situations, issue reduces to whether or not collision is catastrophic

Debris Production Estimation: Historical Conjunction Profiling

- **Procedure run against portion of NASA conjunction database**
  - LEO conjunctions from January to June 2016
  - 14,000 unique events for which secondary a debris object with established RCS
    - CDM with largest Pc taken as event representative
  - 100,000 Monte Carlo samples of estimated # of debris pieces, per event
- **Summarized by percentile point**
  - CDF curves for 50^{th}, 75^{th}, 90^{th}, and 95^{th} percentile of each event's 100,000 results
- **Graph morphology**
  - Flattened and then suddenly vertical behavior indicates transition to catastrophic collision
  - 50% of events do this at the 95^{th} percentile; about 30% do at the 90^{th} percentile
  - If C_D span increased to 2.1 – 4.0, percentages drop from ~8-10%

Debris Production Estimation: Historical Conjunction Profiling Results



Low-Debris-Production Cases: Pc Threshold Alterations

- **95% threshold seems reasonable starting point for separation**
  - Conservative—if one-in-twenty chance of large debris production, then treated as a large debris case
  - About half of profiled events are given this designation, so a good separator of events into two types
    - Although far from all ever became serious events
- **Current Pc remediation thresholds (1-4 E-04) were generated with the large-debris situation in mind**
  - So small-debris situations should show a leniency from this level
- **For primaries that have difficulty remediating conjunctions, offset is from 0.5 to 1 OoM increased leniency in Pc remediation threshold**
  - Electric propulsion is good example
- **Probably a good initial proposal for low-debris situations**
  - 0.5 to 1 OoM, with exact value determined by experience and owner/operator risk tolerance

Orbital Corridor Population

- **Would seem that satellites in “high-value” corridors deserve additional protection**
  - Geosynchronous, sun-synchronous, Molniya—greatly facilitate certain missions
  - Debris population in these orbits would seem more injurious and therefore should engender more risk-adverse posture
- **Not as straightforward in practice**
  - Sun-synchronous can be conceived in a variety of ways
  - Debris at higher orbits pollute lower ones (both immediately and eventually through decay), so this would have to be considered as well
    - Although ~100km lower than Fengyun 1C and Iridium-COSMOS, half of A-Train conjunction events against debris from these two collisions
    - “Protected Zones” about orbits would thus need to become excessively large
- **Geosynchronous orbit the exception**
  - Debris in GEO will remain for a very long time and pass a number of payloads as it moves toward and librates about one of the two libration points
  - Due to persistent threat, should not abate Pc threshold for small-debris cases

Proposed Consequence Construct

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

- **X is the current Pc remediation threshold (usually ~1E-04)**
- **X abated by 0.5 to 1 OoM for low-debris collisions in LEO and HEO**
  - Perhaps 5E-04 to 1E-03
- **No corresponding abatement in GEO, due to debris persistence and ease of orbital corridor pollution**

Future Work

- **Construct is merely CATAC initial proposal**
  - Will be refined over the next 12 months with additional studies
- **Planned future work**
  - More comprehensive error analysis on satellite frontal area estimation
    - Perhaps using cubesats as an additional dataset, since many have known dimensions
  - More comprehensive error analysis on satellite drag coefficient estimation
    - Better understanding of debris shape and area-to-mass distributions for small debris
  - Further refinement of actual construct to be used for operational CA