An Operational Algorithm for Evaluating Satellite Collision Consequence

2019 AAS/AIAA Astrodynamics Specialist Conference

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INTRODUCTION

Motivation [1 of 2]

- **Collision risk assessment approaches are largely based on the Kaplan construct**
- **Collision risk is a combination of event likelihood and event consequence**
- **Conjunction Assessment has only partially followed this approach**
  - Large bodies of work exist on methods to establish event likelihood
  - Most operators treat collision consequence as static—all potential conjunctions are regarded as lethal to the operational satellite
- **In earlier assessments, with relatively few conjunctions, static concept of collision consequence was acceptable**
- **In the current operational environment, this approach needs re-examination**
  - Conjunction frequency is increasing
  - Deployment of USAF Space Fence radar could drastically increase space object catalog
  - Consideration of the consequences of a prospective conjunction could reduce the scope of conjunction remediation actions

Motivation [2 of 2]

- **Protection of primary asset**
  - Some potential collisions could conceivably leave a primary asset crippled, but still functional
    - “Glancing blow” or injury/degradation to part of solar array
  - However, current capabilities preclude determination of a collision of this type
  - Hence, all conjunctions should be presumed as at a minimum, “lethal”
- **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 conjunctions have significant variability in debris-production potential dependent on event geometry and the relative masses of the objects
  - A construct that can categorize conjunctions by potential debris production can thus be of considerable benefit

Previous/Present Work

- **Previous effort* assembled basics of debris production calculation as research article**
- **Present effort provided several enhancements**
  - Improved algorithm (indicated in subsequent slides)
  - Performed expanded testing against additional test sets
  - Assembled parameter recommendations for operational use

* Hejduk, M., Laporte, F., Moury, M., Kelso, T.S., Newman, L., Shepperd, R. "Consideration of Collision "Consequence" in Satellite Conjunction Assessment and Risk Analysis, International Symposium on Space Flight Dynamics, Matsuyama, Japan, 2017.

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**
- **Catastrophic events produce significantly more debris**
- **There are likely intermediate cases, but this is the accepted ODPO distinction**
- **ODPO prescribed methodology for distinguishing between cases: ratio of relative kinetic energy of smaller object to mass of larger object**

$$\frac{M_s V_{rel}^2}{2M_p} > 40{,}000 \frac{J}{kg}$$

  – If ratio exceeds 40,000 Joules / kg, then collision is catastrophic

Debris Generation Prediction

- **NASA ODPO EVOLVE 4.0 model contains a relationship for the number of pieces greater than a certain size generated by a collision dependent on collision type**

$$N(L_c) = \begin{cases} 0.1(V_{rel}M_s)^{0.75}L_c^{-1.71}, & \frac{M_s V_{rel}^2}{2M_p} \leq 40{,}000 \\ 0.1\left(M_s + M_p\right)^{0.75}L_c^{-1.71}, & \frac{M_s V_{rel}^2}{2M_p} > 40{,}000 \end{cases}$$

  - L_c is the characteristic length (in meters) above which one is interested in the number of pieces;
    - a reasonable assumption of the threshold at which to this would be is 0.05m, which is near the smallest characteristic length capable of being tracked

- **To assess this, the following are needed**
  - Conjunction velocity – easily obtained from orbital states
  - Primary object mass – known from mission parameters
  - Secondary object mass – requires estimation method as most conjunctions involve debris objects

Mass Estimation Procedure: Estimating Needed Parameters

- **Secondary object mass is required for catastrophic/non-catastrophic assessment**
  - As well as predicted debris generation from prospective collisions
  - For most conjunctions, mass values will have to be estimated
- **Masses may be estimated from the ballistic coefficient solution**
  - The ballistic coefficient (B) is given by:

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

  - If ballistic coefficient, drag coefficient, and frontal area can be reasonably estimated, then satellite mass (M) can be predicted from above relation
  - Given imprecisions for many of these parameters, it is best to define a PDF for each and thus generate an estimated mass PDF using a sampling strategy

Mass Estimation Procedure: Estimating Ballistic Coefficient (B)

- **Conjunction Data Message (CDM) for particular events give information about the BC for primary and secondary objects**
  - Estimate of mean value (B_μ)
  - Estimation variance (B_σ) from covariance matrix
- **A set of random BC values is easily generated by N(B_μ, B_σ)**

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

Mass Estimation Procedure : Estimating Drag Coefficient (C_D) (New Work)

- **Because ballistic coefficient is 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
- **Recently work has been performed using CFD analyses to analyze drag coefficients for several baseline object configurations at different operational altitudes**
  - For cuboid satellites, Walker et. al.[ii] demonstrated several dependencies for C_d estimation, but this research aimed to utilize the relation between exospheric temperature and C_d (figure 8)
- **For current approach, mean C_D values were generated based on the exospheric temperature relation**
- **Then a relative uncertainty of 5% was applied**
- **At this point, a set of random C_D values are generated by N($C_{D\mu}$, $C_{D\sigma}$)**

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

[ii] Walker, A., Mehta, P., Koller, J., “Drag Coefficient Model Using Cercignani-Lampis-Lord Gas-Surface Interaction Model”, Journal of Spacecraft and Rockets, Vol. 51, No. 5 (2014), pp. 1544-1563.

Cross Sectional Area (A) Estimation Procedure [1 of 2]

- **Satellite areas may be estimated from sensor signature data**
  - This approach focuses on radar cross-section (RCS) as opposed to satellite visual magnitude, since emphasis in this analysis is LEO debris
- **RCS has units of area, but only under special circumstances can this be roughly equated to satellite physical area**
- **NASA's ODPO developed the Size Estimation Model (SEM) to facilitate mapping between RCS and satellite characteristic length**
  - This model is based on an exploded satellite in vacuum chamber
  - Researchers then determined the characteristic dimension of each piece, took RCS measurements on each piece, and effected theory-enabled fit of data

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

Cross Sectional Area (A) Estimation Procedure [2 of 2]

- To match the number of samples generated using the B and C_d methodology, samples of RCS are generated using a Swerling Type III distribution with median RCS values as reported from a CDM
- The ODPO SEM is then used to determined the characteristic length of each RCS sample, L_c
- From this characteristic length, a cross sectional area is approximated assuming a circular cross section

$$A = \frac{\pi L_c^2}{4}$$

- Using the above samples of B, C_d, and A, a set of samples and the accompanying PDF for the object mass are generated

Satellite Size Estimation Validation (New Work)

- **Initial validation was performed using a set of 24 NaK spheres**
  - This set is re-examined here
- **To additionally validate this approach, a large set of NanoSats for a range of operational altitudes were examined**
- **Initial data set comprised of 1000 NanoSats**
- **Pared down to 371 based on specification availability, launch successes, and CDM availability in operational database**
- **Satellite specifications give concrete dimensions of satellites as well as their accompanying, true masses (M)**
- **The frontal areas for cuboid satellites were approximated using the satellite dimensions as follows:**

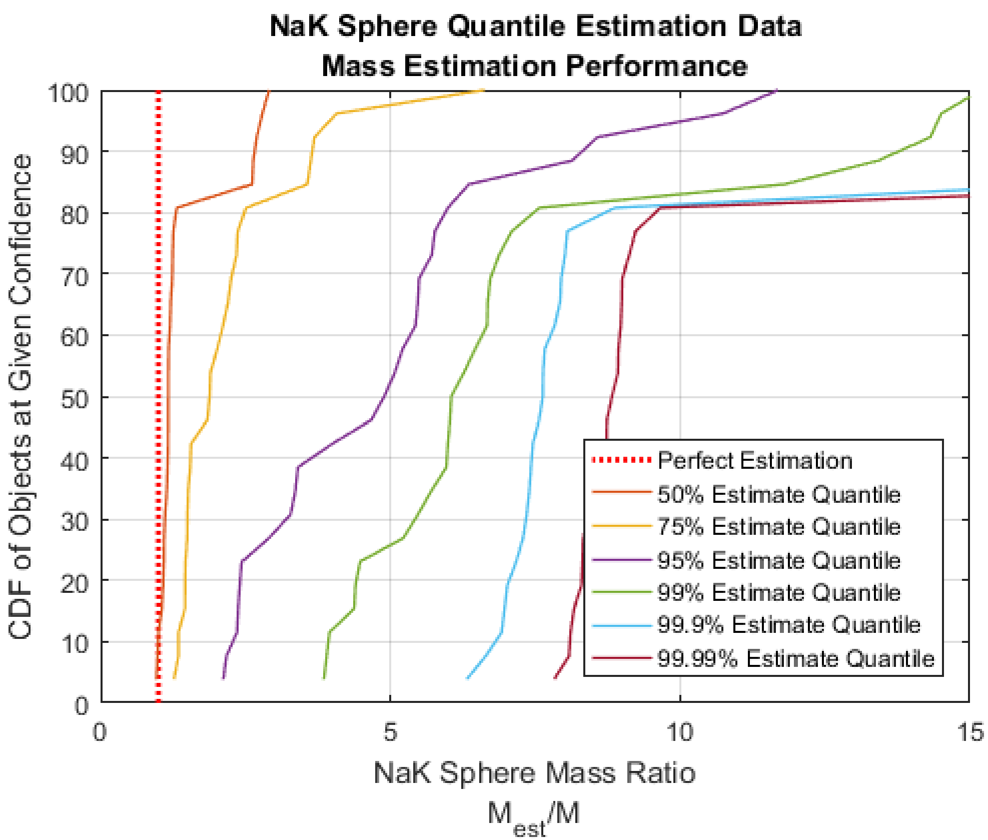
$$A_{total} = \frac{(A_{xy} + A_{yz} + A_{xz})}{3}$$

- **The ratio between estimated values and truth values is then examined to assess the validity of this mass estimation approach**
- **The percentile (quantile) level at which this ratio is conservative is of import**
  - It is desired to overestimate mass in order to yield a conservative (high) debris count

ANALYSIS

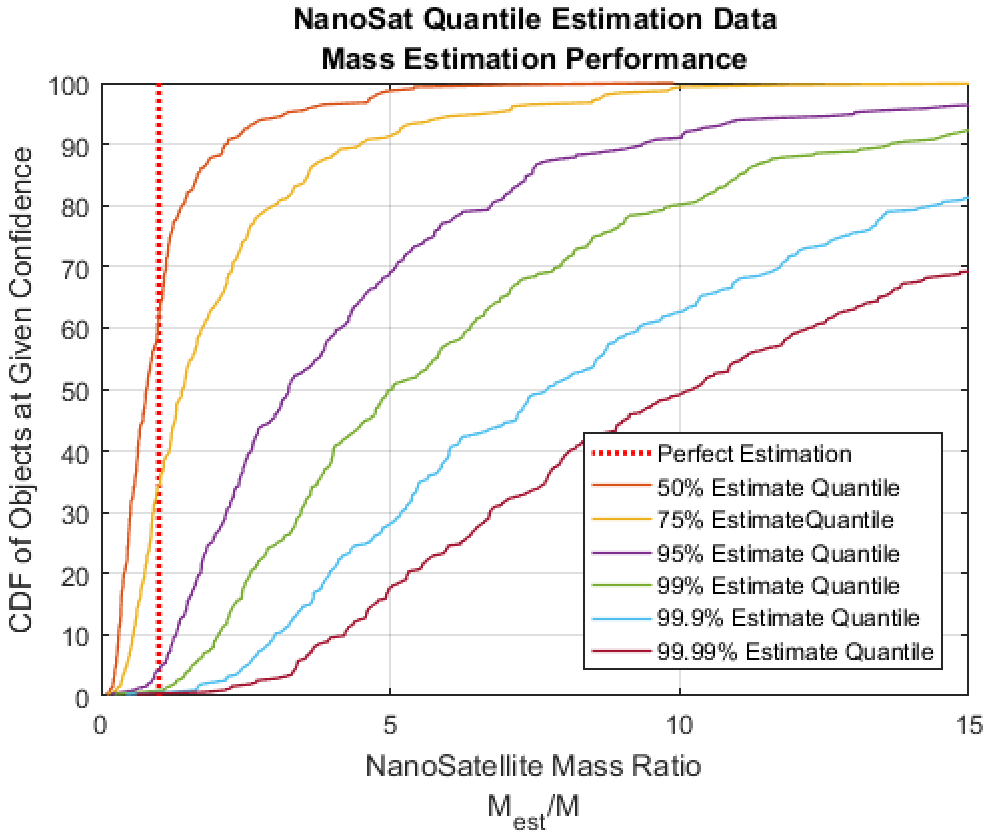
NaK Coolant Sphere Mass Estimation Validation

- It is desired that all results to have $M_{est} / M > 1$
- For spherical objects, a mass estimation quantile of 75% would be sufficient
- This would maintain a conservative mass estimation for collision nature
- Satellite operators can rarely be so assured of the satellite shape
- Hence analysis for more irregular objects is required



NanoSat Size Estimation Validation

- An estimation quantile is desired such that an operator would be reasonably sure of the object mass being overestimated
- A few outliers drive this quantile far above the 75th percentile observed in the NaK spheres
- It is recommended to use the 99.9th percentile of mass estimation for collision consequence assessment using the prescribed methodology



Mass Estimation Quantile	Percent of NanoSatellite Masses Underestimated
50%	64.01%
75%	32.33%
95%	5.08%
99%	1.31%
99.9%	0.52%
99.99%	0.40%

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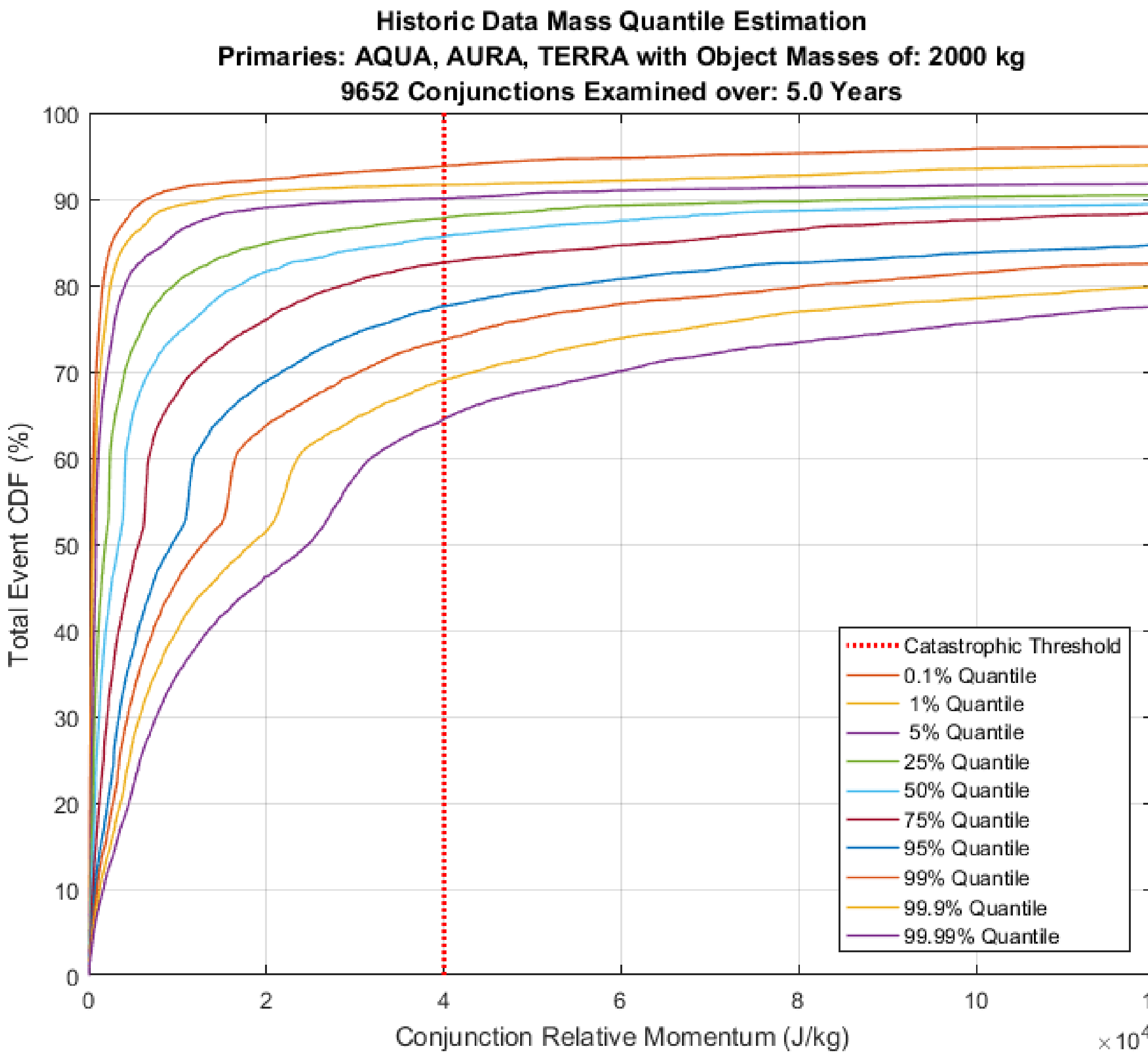
Historic Catastrophic Collision Rate

- **This mass quantile approach was then applied to a series of historical conjunctions**
  - 3 A-Train Satellites
  - ~700 km in altitude
  - 5 Years of conjunctions
  - 9652 discrete events
  - 2000 kg primary mass
- **Amount of non-catastrophic events may be assessed on a mass estimation quantile basis**
- **Using recommended quantile of 99.9%, 69.03% of all events were non-catastrophic in nature**



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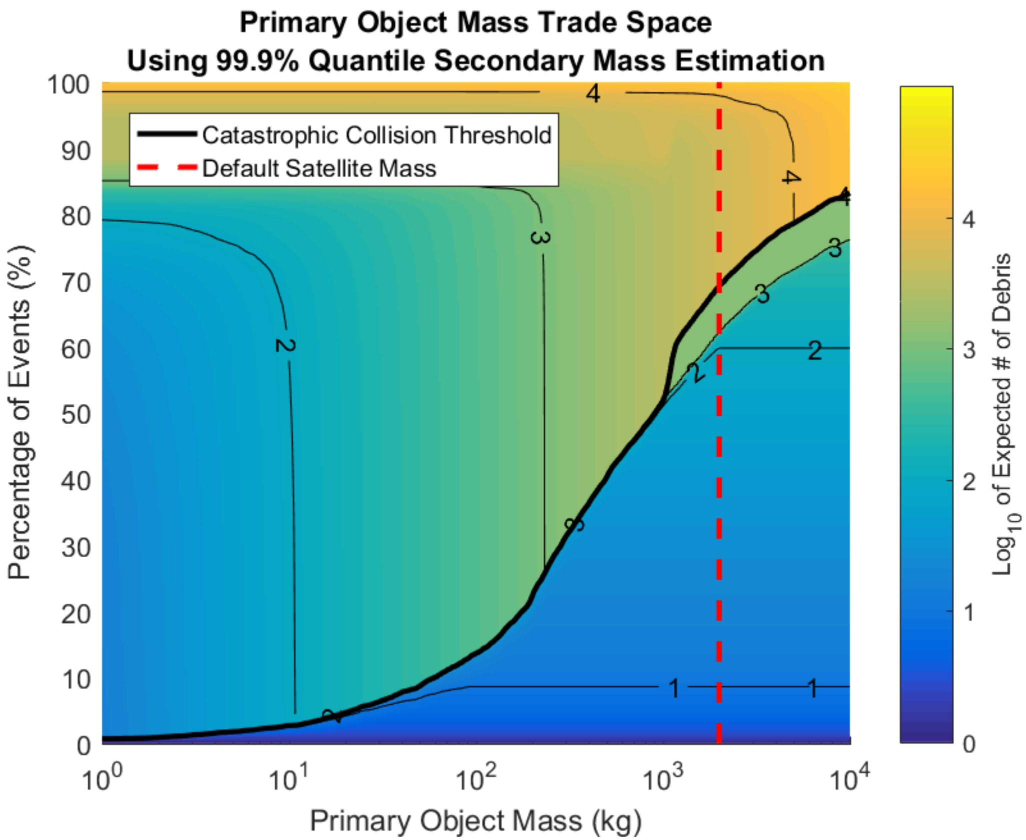
Primary Object Mass Trade Space

- **Debris production potential was examined using varying primary object masses**
  - Debris production was limited to objects larger than 5 cm
- **There is a marked, order of magnitude increase in debris potential as the "Catastrophic" threshold is passed**
- **For a primary object mass of 2000 kg, 60% of all conjunctions would produce 100 debris pieces or fewer larger than 5 cm**



CONCLUSIONS AND RECOMMENDATIONS

Conclusions and Recommendations

- **Conjunctions likely to be catastrophic in nature should be given higher priority in maneuver planning activities than those that are non-catastrophic**
- **Non-catastrophic conjunctions may be allowed further leniency in the CA process and perhaps less stringent RMM thresholds**
- **To determine the catastrophic/non-catastrophic nature of collisions, use of a mass estimation quantile is recommended**
  - This quantile should be conservative in that it should overestimate the object mass in most cases
  - **Recommended quantile: 99.9%**
- **Should operators elect to triage non-catastrophic conjunctions to a lower priority, maneuver planning activities may be significantly reduced due to a large percentage of historical events being considered non-catastrophic**
  - ~69% of events encountered by A-Train satellites fall into this category using the given quantile recommendation
- **More robust methods of evaluating collision consequence may be implemented by examining debris production potential**
  - ~60% of events encountered by A-Train satellites would produce 100 debris objects or fewer using this criteria

Future Work

- **Re-examine and further refine drag coefficient estimation methodologies**
- **Examine and recommend debris production potential thresholds based on operational considerations and orbit regime protection**
- **Examine orbital lifetime distributions and decay rates of potential debris fields**

QUESTIONS