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INTRODUCTION
• 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
• 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

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

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

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

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

- \(L_c\) 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 ($B_\mu$)
  – Estimation variance ($B_\sigma$) from covariance matrix

• A set of random BC values is easily generated by $N( B_\mu, B_\sigma )$

$$B = C_D \frac{A}{M}$$
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.\textsuperscript{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 $N( C_{D\mu}, C_{D\sigma} )$

\[ B = \frac{C_D}{M} \]

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

\[ B = C_D \frac{A}{M} \]
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
• It is desired that all results to have $M_{\text{est}} / M > 1$
• 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
• 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
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.
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