NASA Conjunction Assessment Organizational Approach and the Associated Determination of Screening Volume Sizes

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NASA ROBOTIC CARA

www.nasa.gov
NASA’s Process: CARA

- NASA is committed to safety of flight for all of its operational assets
  - Performed by CARA at NASA GSFC for robotic satellites
    - Focus of this briefing
  - Performed by TOPO at NASA JSC for human spaceflight
- The Conjunction Assessment Risk Analysis (CARA) was stood up to offer this service to all NASA robotic satellites
  - Currently provides service to ~70 operational satellites
    - NASA unmanned operational assets
    - Other USG assets (USGS, USAF, NOAA)
    - International partner assets
NASA has performed CA for 25 years. Initial USSTRATCOM capability developed with NASA.
Mission Context: Number of Conjunctions in LEO

Number of Conjunctions per Month within +/- 0.5x5x5-km Volume, All LEO Primary Objects

- Jason-1 / TOPEX Repeating Conjunction
- Landsat-5 / A-Train Crossover
- Addition of NOAA & DMSP Satellites
- Chinese ASAT 11 Jan 2007
- Chinese ASAT 10 Feb 2009
- Iridium/Cosmos Collision 11 Jan 2007
- Iridium/Cosmos Collision 10 Feb 2009
- NPR requiring all operational assets, not just maneuverable May 2009
- GRACE Satellite Swap

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GRACE Satellite Swap
In 2014, 13.7% of the planned maneuvers resulted in maneuvers.
Conjunction Assessment (CA) is the process of identifying close approaches between two orbiting objects; sometimes called conjunction “screening”.

The Joint Space Operations Center (JSpOC) – a USAF unit at Vandenberg AFB, maintains the high accuracy catalog of space objects, screens CARA-supported assets against the catalog, performs OD/tasking, and generates close approach data.

CA Risk Analysis (CARA) is the process of assessing collision risk and assisting satellites plan maneuvers to mitigate that risk, if warranted.

The CARA Team at NASA-GSFC provides CARA for all NASA operational robotic satellites, as well as a service provider for some other external agency/organizations.

Collision Avoidance (COLA) is the process of executing mitigative action, typically in the form of an orbital maneuver, to reduce collision risk due to a conjunction.

Each satellite Owner/Operator (O/O) – mission management, flight dynamics, and flight operations – are responsible for making maneuver decisions and executing the maneuvers.
CARA Operational Process:  
Close Approach Predictions at the JSpOC

- The JSpOC maintains an accurate state for all trackable objects
- In support of CARA, the Goddard-dedicated Orbital Safety Analysts (OSA)
  - Perform routine screenings – 2x day for LEO, 1x for GEO/HEO
  - Against JSpOC’s Astrodynamics Support Workstation (ASW) solution and the O/O solution if available
  - Inspect orbit determination; perform manual orbit determination, if warranted
  - Adjudicate tasking level of secondary objects; request increased tasking, if warranted
  - Generate and deliver necessary data products
- JSpOC is staffed by Goddard-dedicated OSA 18 hours/day

The Screening Duration is the “lookout” period of time for which conjunctions are identified. This is 7 days for LEO assets and 10 days for GEO/HEO assets.

The Screening Volume is the geometric volume placed around the asset during the conjunction screening process; any objects that violate this volume trigger data products to be generated and delivered. The screening volumes are re-sized annually by CARA using a 95% capture of the relative uncertainties in each orbital regime based two-year moving window historical conjunction data.
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Approach described in later charts

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CARA Operational Process: Collision Risk Analysis at NASA-GSFC

- CARA is responsible for assessing, communicating, and assisting with mitigation of on-orbit collision risk
- As data is received, the CARA system automatically processes that data, and generates & delivers
  - CARA Summary Reports to O/O
  - Work List to JSpOC OSAs
- CARA team performs routine risk analysis
  - Pc; Pc sensitivity
  - Conjunction Geometry
  - OD Evaluation / Solution Consistency
  - Space Weather Sensitivity
  - Maneuver planning & evaluation
- For high-risk conjunctions, CARA builds and delivers a High Interest Event (HIE) briefing with detailed analyses, and planning & decision information

The Collision Probability ($P_c$) is the probability that, given the uncertainty in the two objects' positions as described by their covariance matrix, that the actual miss distance is less than the hard-body region.

$$P_c = \frac{1}{2\pi[\text{det}(C)]^{1/2}} \int_{A} e^{-\frac{1}{2}x^T C^{-1} x} dA$$
Maneuver Planning

- A trade-space contour plot shows the effect that a range of phase times and delta-v magnitudes have on miss distance
  - Single conjunction event (top)
  - Multiple events (bottom)
- Assists with initial maneuver planning
  - Save time-expensive iteration cycles for high fidelity maneuver planning
  - Does not presume any constraints about satellite maneuver capability or conjunction mitigation strategies—allows flight support teams to decide on course of action
JSpOC CA Screening and CDM Generation Approach

- First, perform screening to find close approaches to primary
  - Filter out secondaries that cannot possibly collide with primary
  - Generate ephemerides for primary and secondaries that are possible threats
  - Construct screening volume about primary
  - “Fly” the ellipsoid along the primary’s ephemeris
    - 7 days for LEO
    - 10 days for HEO/GEO
  - Any penetrations constitute possible conjunctions
- Once conjunctions identified, generate initial risk information for each
  - Determine time of closest approach (TCA)
  - Calculate probability of collision (Pc)
- Because gatekeeper for further processing, screening portion important
  - Size of volume determines the objects discovered
Screening Volume Sizing Approach: Constituent Elements

- Appropriate sampling dataset
- Screening volume sizing definition
- CDM data use: assumptions
- Screening volume shaping approaches
- Presentation of results
Screening Volume Sizing Approach: Appropriate Sampling Dataset (1 of 2)

- Historical CDMs suggest themselves as investigation dataset
  - Contain conjunction information, so number of analytical criteria available
  - However, dataset a function of past screening volume size—circularity risk
- Limit dataset to events that showed some propensity for severity
  - Screening volumes to capture certain percentage of potentially serious events
  - Highest $P_c$ observed during event good indication of this
- However, set $P_c$ at fairly “generous” value to ensure consideration of nearly all potentially worrisome events
  - $P_c > 0$ (for MATLAB numerical integrator, equivalent to $P_c > 1E-324$)
  - For 2013-14, about 70% of events contained a $P_c > 0$
    - About 56% (333,000) of all CDMs
Screening Volume Sizing Approach: Appropriate Sampling Dataset (2 of 2)

- Divide primaries into orbital regimes and analyze CDMs from each orbital regime separately:

<table>
<thead>
<tr>
<th>Orbital Regime</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEO #1</td>
<td>Perigee ≤ 500 km &amp; Eccentricity &lt; 0.25</td>
</tr>
<tr>
<td>LEO #2</td>
<td>500 km &lt; Perigee ≤ 750 km &amp; Eccentricity &lt; 0.25</td>
</tr>
<tr>
<td>LEO #3</td>
<td>750 km &lt; Perigee ≤ 1200 km &amp; Eccentricity &lt; 0.25</td>
</tr>
<tr>
<td>LEO #4</td>
<td>1200 km &lt; Perigee ≤ 2000 km &amp; Eccentricity &lt; 0.25</td>
</tr>
<tr>
<td>MEO</td>
<td>600 min &lt; Period &lt; 800 min &amp; Eccentricity &lt; 0.25</td>
</tr>
<tr>
<td>GEO</td>
<td>1300 min &lt; Period &lt; 1800 min &amp; Eccentricity &lt; 0.25 &amp; Inclination &lt; 35º</td>
</tr>
<tr>
<td>HEO #1</td>
<td>Perigee &lt; 2000 km &amp; Eccentricity &gt; 0.25</td>
</tr>
<tr>
<td>HEO #2</td>
<td>Perigee &gt; 2000 km &amp; Eccentricity &gt; 0.25</td>
</tr>
</tbody>
</table>

- Divide CDMs for each primary into different “Time to TCA” bins
  - Map roughly to propagation times
  - Proposed bins are 0-2 days, 3-4 days, and 5-7 days
Screening Volume Sizing: Definitional Premise

- If a particular CDM were to represent an actual collision, would want screening volume sized to capture this event x% of the time
  - Since screenings run twice per day seven days into the future, some flexibility in the value of “x” to still get a very high capture percentage
  - If screenings were not correlated events, formula for total probability of collision (TPc) could be used
    - \( TPc = 1 - \prod (1 - x)^n \); which would push the total probability rapidly to unity
  - However, subsequent screenings are correlated events, so cumulative effect will be less than this theoretical maximum
- Probably want each screening’s capture percentage somewhere in the range of 75 – 95%
  - In explicit language: “If the two objects were actually to collide, would want to find this event with a single screening x% of the time”
  - This should provide a reasonably high total probability from multiple screenings over several days
CDM Data Use Assumption #1: Zero-Miss Alteration

• CDM represents a close approach between two satellites, but in nearly all cases not a reported actual collision at the mean value
  – i.e., there is a non-zero miss distance > the combined hard-body radius
• However, a very small change in trajectory (especially several days before TCA) could transform event into a collision
  – This would alter the event so as to drive the miss distance to < HBR
• This “small change” has very little effect on the objects’ covariances
  – Can presume both covariances to be unaltered by it
• Combined primary and secondary covariance thus a statement of the uncertainty of the secondary about the primary’s position in the case of an actual collision
  – Monte Carlo draws on such a covariance yield an uncertainty “cloud” of positions about the primary that would still yield a collision (at the mean value)
  – Screening volume should be sized to capture x% of such a set of position uncertainties
CDM Data Use Assumption #2: Relative Velocity Component Elimination

- If conjunction is high velocity and short duration, a collision, should it occur, will take place in “conjunction plane”
  - Plane normal to the two satellites’ relative velocity vector
- Basis for 2-d probability of collision calculation paradigm
  - Collision geometry and combined covariance projected into this plane
  - Covariance components in relative velocity direction contribute nothing to the Pc calculation—they lie outside of this plane
- Can take advantage of this fact in setting screening volume sizes
  - Can eliminate relative velocity components of combined covariance
    - These components will not affect the Pc
- Will have the effect of shrinking the screening volume size necessary to achieve a certain capture percentage
Screening Volume Sizing Procedure

- Assemble set of CDMs for particular orbit regime and time group
- Combine primary and secondary covariances for each CDM and project into conjunction plane
- Use projected covariances to create Y perturbation points for each; rotate these points back to 3-d coordinate frame
  - Present analysis experimenting with using between 5,000 to 10,000 perturbation points per CDM; limited by machine memory
- Construct screening volumes that capture x% of this set of points
  - Apply nested application of radial and then cross-track sizes
  - For each, use iterative solution to determine size of in-track component that brings the volume to a x% capture level (if this is possible)
  - Example: construct an ellipsoid (centered at origin in RIC system) that has a radial component of 1km and an in-track component of 20km
    - Iterate to find the in-track component that captures 90% of the perturbation points
- Construct a trade-space of these results
Sample Output: Orbit Regime 1 (High Drag)

- Y-axis radial component of screening volume; X-axis is cross-track
- Color ("Z-axis") is in-track component
- All axes in log space
- Symbols show 2013 and 2014 screening volume sizes
- Many different ways to achieve desired capture percentage
  - Can thus consider other factors, such as desired volume shape
Current Status

• Analysis continuing
  – CDM database being expanded
• Final results should be complete by this summer
  – Will present results and way forward at Users Forum