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

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International CA Risk Assessment Workshop
19-20 MAY 2015

NASA ROBOTIC CARA
www.nasa.gov
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

Chinese ASAT 11 Jan 2007

Iridium/Cosmos Collision 10 Feb 2009

Addition of NOAA & DMSP Satellites

NPR requiring all operational assets, not just maneuverable May 2009

GRACE Satellite Swap

Jason-1 / TOPEX Repeating Conjunction

Landsat-5 / A-Train Crossover

5
In 2014, 13.7% of the planned maneuvers resulted in maneuvers.
The CARA Process Helps Manage On-Orbit Collision Risk

**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

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

$$P_c = \frac{1}{2\pi[\det(C)]^{1/2}} \int_{A} e^{-\frac{1}{2}x'C^{-1}x} \, dA$$
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 Pc observed during event good indication of this
- However, set Pc at fairly “generous” value to ensure consideration of nearly all potentially worrisome events
  - Pc > 0 (for MATLAB numerical integrator, equivalent to Pc > 1E-324)
  - For 2013-14, about 70% of events contained a Pc > 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; 35°</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 a 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