NASA Conjunction Assessment Risk Analysis (CARA)

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NASA’s Process: CARA

- NASA performs conjunction assessment risk analysis for safety of flight of all of its operational assets
  - Performed by CARA at NASA GSFC for robotic satellites
  - 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 ~65 operational satellites
    - NASA unmanned assets
    - Other agency assets such as NOAA, DMSP
    - Foreign partner assets
    - Commercial assets
NASA Conjunction Assessment History

1986: Challenger accident

1988: Space Shuttle Discovery Return to Flight; Box method used for CA; later Shuttle adopts Pc method

1992: NASA begins Pc development for ISS CA

1996: NASA begins conjunction assessment of Mir space station

1998: ISS First Element Launch

1999: First attempted ISS DAM attempted and fails; a few months later first ISS DAM successfully executed

1990s – present: NASA works with USSTRATCOM to develop tools, data exchange formats, improve processes for catalog maintenance and CA

2005: NASA begins CA for robotic missions

Present: NASA continues work with USSTRATCOM to maintain high quality CA for human spaceflight and robotic missions

NASA has performed CA for 29 years. Initial USSTRATCOM capability developed with NASA.
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 18th Space Control Squadron at 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
  – Note that these solutions use non-cooperative tracking from the Space Surveillance Network (SSN), and do not contain maneuvers
• In support of CARA, the CARA-dedicated Orbital Safety Analysts (OSA)
  – Perform routine screenings – 3x day for LEO, 2x for GEO/HEO
    • Against JSpOC’s Astrodynamics Support Workstation (ASW) solution and for some missions the O/O solution as well
  – 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 CARA-dedicated OSAs 20 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.
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 sent to CARA 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 (Pc) 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.
Mission Context: Number of Conjunctions in LEO

Unique Events within 0.5x5x5-km Volume by Object Type, LEO

2. Iridium/Cosmos Collision: 10 Feb 2009
3. Jason-1 / TOPEX Repeating Conjunction
4. Landsat-5 / A-Train Crossover
5. NPR requiring all operational assets, not just maneuverable: May 2009
6. Addition of NOAA & DMSP Satellites
7. SHY Changes
8. GRACE Satellite Re-positioning

NASA CARA
Collision Avoidance Maneuvers History
## CARA Summary Report: Event Summary

### A. High Risk Conjunction Events [Collision Probability >= 4.4e-4]

<table>
<thead>
<tr>
<th>Days to TCA</th>
<th>TCA (GMT)</th>
<th>Secondary Object</th>
<th>Primary Ephem Source</th>
<th>Secondary Ephem Source</th>
<th>Screening Epoch (GMT)</th>
<th>Miss [m]</th>
<th>R [m]</th>
<th>I [m]</th>
<th>C [m]</th>
<th>Tracked Since Previous OCM?</th>
<th>Pc Above Mission Threshold?</th>
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</thead>
<tbody>
<tr>
<td>4.2</td>
<td>8 Nov 2015 04:45:41</td>
<td>TITAN 3C TRANSTAGE DEB (01722)</td>
<td>ASW</td>
<td>ASW</td>
<td>3 Nov 2015 19:45:32</td>
<td>783.0</td>
<td>22.8</td>
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<td>O/O + ASW cov.</td>
<td>ASW</td>
<td>3 Nov 2015 19:38:46</td>
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<td>81.1</td>
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<td>2.03e-2 (1:49)</td>
</tr>
</tbody>
</table>

### B. Monitor Conjunction Events [1e-7 <= Collision Probability < 4.4e-4]

<table>
<thead>
<tr>
<th>Days to TCA</th>
<th>TCA (GMT)</th>
<th>Secondary Object</th>
<th>Primary Ephem Source</th>
<th>Secondary Ephem Source</th>
<th>Screening Epoch (GMT)</th>
<th>Miss [m]</th>
<th>R [m]</th>
<th>I [m]</th>
<th>C [m]</th>
<th>Tracked Since Previous OCM?</th>
<th>Pc Above Mission Threshold?</th>
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</thead>
<tbody>
<tr>
<td>4.6</td>
<td>8 Nov 2015 15:04:53</td>
<td>UNKNOWN (87789)</td>
<td>ASW</td>
<td>ASW</td>
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<td>1224</td>
<td>9424</td>
<td>N</td>
<td>6.38e-7 (1:2M)</td>
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</tbody>
</table>

### C. Low Risk Conjunction Events [Collision Probability < 1e-7]

<table>
<thead>
<tr>
<th>Days to TCA</th>
<th>TCA (GMT)</th>
<th>Secondary Object</th>
<th>Primary Ephem Source</th>
<th>Secondary Ephem Source</th>
<th>Screening Epoch (GMT)</th>
<th>Miss [m]</th>
<th>R [m]</th>
<th>I [m]</th>
<th>C [m]</th>
<th>Tracked Since Previous OCM?</th>
<th>Pc Above Mission Threshold?</th>
</tr>
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<tbody>
<tr>
<td>4.5</td>
<td>8 Nov 2015 13:25:58</td>
<td>UNKNOWN (87789)</td>
<td>ASW</td>
<td>ASW</td>
<td>3 Nov 2015 19:46:16</td>
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<td>111.2</td>
<td>1933</td>
<td>14730</td>
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<td>0.00e00</td>
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<td>4.5</td>
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<td>O/O + ASW cov.</td>
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<td>3 Nov 2015 19:46:18</td>
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<td>-12144</td>
<td>N</td>
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</tbody>
</table>
Conjunction Event Details - GCOM-W1 (38337) vs. TITAN 3C TRANSTAGE DEB (1722)

| Days to TCA | TCA (GMT) | Secondary Object | Primary Ephem Source | Secondary Ephem Source | Screening Epoch (GMT) | Miss [m] | R [m] | l [m] | C [m] | Tracked Since Previous OC? | Pc | Above Mission Threshold?
|-------------|-----------|------------------|----------------------|------------------------|------------------------|----------|-------|-------|-------|---------------------------|----|---------------------------
| 4.2         | 8 Nov 2015 04:45:41 | TITAN 3C TRANSTAGE DEB (1722) | ASW | ASW | 3 Nov 2015 19:45:32 | 783.0 | 22.8 | 334.1 | 708.4 | Y | 4.93e-4 (126) | --- |
| 4.2         | 8 Nov 2015 01:45:41 | GCOM-W1 (38337) | ASW | ASW | 3 Nov 2015 19:48:46 | 91.0 | 17.7 | 37.6 | 81.1 | Y | 2.03e-2 (169) | --- |

1. Summary header
   - Days to TCA
   - Secondary Name & ID
   - Screening Epoch
   - Latest Miss Distance
   - Latest Pc & Risk Characterization

2. Pc History and Event Flags
   - Latest secondary object OD & tracking information
   - Avg Tracks / Day
   - Time Since Last Observation
   - Total Propagation Time of vector
   - Single Station Indicator

3. Secondary Object OD Information
   - Avg. Tracks / Day: 4.1
   - Time Since Last Observation: < 24 hrs
   - Total Propagation Time: ~4 days

4. Maneuver information
   - Maneuver Epoch: 2015-10-28 01:23 Z
   - Magnitude [m/s]: 0.028000
   - Duration [s]: N/A
   - Type: DARU

5. Filenames of O/O Products used
   - Most Recent O/O Ephemeris File: SOEMP_PRL_GCOMW1_F20151110_000000_T20151111_000000
   - Ephemeris File End: 2015-11-01 00:00:00
   - Most Recent O/O Covariance File: N/A

6. ASW Miss Component History
   - OO Miss Component History
CARA Summary Report: Continued

1. ASW and O/O Conjunction Planes
2. Miss History
3. ASW and O/O Event Geometry

**Miss History**

<table>
<thead>
<tr>
<th>Date [GMT]</th>
<th>Miss (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11/01</td>
<td>1000</td>
</tr>
<tr>
<td>11/03</td>
<td>1200</td>
</tr>
<tr>
<td>11/05</td>
<td>1400</td>
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<tr>
<td>11/07</td>
<td>1600</td>
</tr>
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</table>

**Event Geometry**

<table>
<thead>
<tr>
<th>Event</th>
<th>ASW</th>
<th>O/O</th>
</tr>
</thead>
<tbody>
<tr>
<td>F-Value (scaled/unscaled)</td>
<td>8.0 / 9.1</td>
<td>N/A</td>
</tr>
<tr>
<td>Radial Sigma [m]</td>
<td>12.7</td>
<td>12.6</td>
</tr>
<tr>
<td>Intrack Sigma [m]</td>
<td>161.9</td>
<td>130.0</td>
</tr>
<tr>
<td>Crossover Sigma [m]</td>
<td>346.4</td>
<td>278.3</td>
</tr>
<tr>
<td>Relative Velocity [m/s]</td>
<td>13592.0</td>
<td>13592.0</td>
</tr>
<tr>
<td>Approach Angle [deg]</td>
<td>129.9</td>
<td>129.9</td>
</tr>
</tbody>
</table>
OSA Work List

- CARA system automatically generates & delivers a prioritized work list
  - CARA OSAs perform their duties in priority order
  - Ensures limited resources are used effectively – in the order of risk or potential to become high risk
  - Closed-loop process between OSAs and CARA
  - Representative format:

Grouped by Risk using Pc thresholds

1. Aqua vs. 12345
2. Aqua vs. 23456
3. Aqua vs. 34567
4. Aqua vs. 45678
5. Aqua vs. 56789

Rank-ordered within group by increasing OD quality

- Also includes list of recent (for indicating when OD should be cut) and upcoming maneuvers (satisfies NASA maneuver reporting requirement)
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
Continuous Enhancement Process

- CARA is continuously trying to enhance its service offering through analysis
- Recent Enhancements
  - Calculation of 3D Pc
  - Space weather trade space
  - Multiple event maneuver planning
  - Covariance realism and Pc uncertainty
- Current/ongoing areas of inquiry
  - Screening Volume sizing/shaping
  - S-band Fence CA impacts
  - Automated OD quality assessment, covariance quality estimates, and related sensor tasking modification recommendations
  - Pc calculations that accommodate non-Gaussian uncertainty volumes
Future Challenges

- Low / No Thrust Protected Assets
- Space Fence
  - Compensatory algorithm development
  - Advanced risk assessment methods (event aggregation)
  - Non-traditional risk mitigation techniques
  - Threshold Agency Standards
- CubeSats / SmallSats
- Mega Constellations
- Improved Atmospheric Density Modeling (and Uncertainty Quantification)
- Extremely fast non-linear orbit propagation
- Co-location & Systematic Conjunctions
- Space Traffic Management