Status of the NASA Robotic Mission Conjunction Assessment Effort

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Agenda

- Background
- Goddard Stakeholders and Mission Support
- ESC and TDRS Mission Descriptions
- TDRS Conjunction Assessment Process
- ESMO Conjunction Assessment Process
  - Risk Assessment
  - Risk Mitigation
- Recent Operations Experiences
- Statistics Collected for ESC Regime
- Current & Future Analysis Items
• The collision risk due to orbital debris is increasing:
  – ~11,000 tracked objects >1 cm²
  – There have been 3 collisions publicly documented; all events occurred in low earth orbit, 1 near ESC regime
  – Several hundred objects are being added to catalog each year (Ref Liou & Johnson)
• Recent events such as the Chinese ASAT test and the Breeze-M rocket explosion have led to greater community awareness and concern
  – Demonstrates the necessity of an operations concept that includes monitoring, computing and mitigating collision risks
• Routine (daily) close approach predictions are made for numerous DoD and NASA assets
  – Collision risk assessment analysis considered a critical component of orbital safety for DoD
  – NASA currently has no requirement regarding Conjunction Assessment (CA); individual Flight Projects implement programs for risk mitigation using available resources

• Existing NASA CA Programs:
  – NASA/JSC performs CA for Human Space Flight assets 3 times a day
  – NASA/GSFC performs routine assessments for 11 Earth Science Constellation satellites and 9 TDRS satellites
Routine conjunction assessment began in January 2005 for TDRS and Aqua/Aura. Remaining ESC missions added incrementally over 6 month period

- Cheyenne Mountain 1st SPCS NASA GSFC-dedicated Orbital Safety Analysts (OSA) perform screening for Goddard

- Governing Documents are:
  - “Memorandum of Agreement between DoD and NASA for Support to NASA Spaceflight Operations”
  - Support Agreement between Air Force Space Command and Goddard Space Flight Center
  - Interagency Operating Instruction (draft): Describes the products exchanged between 1st SPCS and GSFC
TDRS System Description

- Relay system composed of ground systems and nine spacecraft in geosynchronous orbit positioned at various longitudinal slots about the Earth.
Earth Science Constellations

- Combination of NASA and FSO assets
- Each mission makes its own risk mitigation decisions
- Each mission subject to own maneuverability, comm, and ops concept constraints
• Screenings performed daily (weekends as needed) using the high accuracy (Special Perturbations) catalog
• Predictions are made 7 days into the future.
• Both Owner/Operator and Cheyenne Mountain-derived ephemerides are processed for the primary objects of interest.
  - Any planned maneuvers are modeled in the Owner/Operator ephemerides.
TDRSS CA Process
TDRS CA Process

- All conjunctions predicted to pass within a 40-km stand-off radius of a TDRS are reported by 1SPCS to Stakeholders.
  - Conjunctions with total predicted misses less than 40 km, but greater than 15 km are referred to as "Monitor" conjunctions.
  - Conjunctions with total predicted misses less than 15 km are Alert Conjunctions, and are graded as follows:

<table>
<thead>
<tr>
<th>Alert Condition</th>
<th>Minimum Predicted Separation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yellow</td>
<td>5 km &lt; Total Miss &lt; 15 km</td>
</tr>
<tr>
<td>Orange</td>
<td>2 km &lt; Total Miss &lt; 5 km</td>
</tr>
<tr>
<td>Red</td>
<td>0 km &lt; Total Miss &lt; 2 km</td>
</tr>
</tbody>
</table>

- Orange and Red alert conjunctions are candidates for evasive maneuver planning
  - Screening frequency increased to at least daily

  NASA considers and potentially plans a collision avoidance maneuver

  Space Segment Manager makes the final decision
ESMO CA Process
ESC Safety Volumes

- Three different mission safety volumes define data product delivery from 1st SPCS and data processing from EOS CA team
- The safety volumes are expressed in the primary U VW coordinate frame: U (radial), V (in-track) and W (cross-track)
- **Monitor Volume** (ellipsoid) +/- 2 x 25 x 25 km
  - Largest filter used to initially identify and report potential close approaches
- **Tasking/Alert Volume** (box) +/- 0.5 x 5 x 5 km
  - Serves as a second warning and an elevated level of concern
  - Tasking level on the secondary object is increased (if necessary)
- **Watch Volume** 1 km standoff distance
Data Products from 1st SPCS

• All Monitor Volume violations are summarized in a Conjunction Summary Report and delivered to the CA SFTP server. The Summary Report contains:
  – Time of Closest Approach (TCA)
  – Total Miss Distance
  – Miss Distance Position and Velocity Components in RIC frame

• An Orbital Conjunction Message (OCM) is provided for Tasking/Alert Volume violations. The OCM contains:
  – TCA
  – Asset State/Covariance at TCA
  – Object State/Covariance at TCA
  – Other orbit determination information helpful in performing collision risk assessment.

• Vector Covariance Messages (VCMs) for both objects are provided for Watch Volume violations.
  – VCMs contain epoch state and covariance information
  – Used for maneuver planning
The Collision Assessment System

- Collision Assessment System (CAS) was developed to store and analyze the large volumes of data received.
- CAS is automated and comprised of several elements:
  - Secure File Transfer Protocol Server
  - Parser / Monitor Scripts
  - Database
  - Collision Assessment and Mitigation (CAM) Tool Suite
  - Secure Website
  - Configuration Management System

- 1st SPCS posts data products to the SFTP site.
- CAS automatically parses the data and puts it into the database for trending and use with other tools
- The CAM Tool Suite is run each time new data is received

A summary report is generated containing all pertinent information and delivered to stake-holders.
Collision Assessment and Mitigation Tool Suite

- The CAM Tool Suite is the part of CAS that provides analysis utilities
- The CAM Tool Suite consists of 6 modules:
  1. Conjunction Visualization Script
  2. 2-D Collision Probability Utility
  3. Monte Carlo Simulation
  4. 3-D / Curvilinear Collision Probability Tool
  5. Time History Trending Utility
  6. Collision Avoidance Planning Tool
- The modules are built using FreeFlyer™ and Matlab™
- Output from tools is formatted into a single PDF report for each OCM
Screening Data Processing

• Conjunction Summary Report Processing:
  – Overlap compare computes differences between subsequent solutions for the same close approach
  – 1stSPCS and Owner/Operator solutions are compared
  – Results are posted to the EOS Portal

• A CA Calendar is produced and posted to the Portal
  – Contains close approach predictions of less than 1 km, events having $P_c > 1e-7$, and planned maneuver dates/times.

• CA Analyst examines all data on Portal daily to produce a “watch list” of events warranting further analysis.

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### Sample Watch List

11-01-2006  Conjunction Watch List

<table>
<thead>
<tr>
<th>Primary v Secondary</th>
<th>TCA</th>
<th>Action</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Landsat-5 v 87893</td>
<td>11/02/06 17:25</td>
<td>Not a threat</td>
<td>Large miss distance.</td>
</tr>
<tr>
<td>Landsat-7 v 26181</td>
<td>11/04/06 13:39</td>
<td>Monitor</td>
<td>Will monitor updates to the OD on both objects.</td>
</tr>
<tr>
<td>Terra v 10525</td>
<td>11/04/06 16:43</td>
<td>Not a threat</td>
<td>Large miss distance.</td>
</tr>
<tr>
<td>SAC-C v 22577</td>
<td>11/03/06 10:08</td>
<td>Not a threat</td>
<td>Miss distance is much larger than position uncertainty.</td>
</tr>
<tr>
<td>SAC-C v 81168</td>
<td>11/05/06 17:20</td>
<td>Not a threat</td>
<td>Large miss distance.</td>
</tr>
<tr>
<td>Aura v 478</td>
<td>11/04/06 15:13</td>
<td>Not a threat</td>
<td>Large miss distance.</td>
</tr>
<tr>
<td>Parasol v 82104</td>
<td>11/06/06 21:02</td>
<td>Not a threat</td>
<td>Large miss distance.</td>
</tr>
<tr>
<td>CloudSat v 06173</td>
<td>11/06/06 07:03</td>
<td>Not a threat</td>
<td>Large miss distance.</td>
</tr>
<tr>
<td>CloudSat v 29054</td>
<td>11/06/06 21:50</td>
<td>Not a threat</td>
<td>Large miss distance.</td>
</tr>
</tbody>
</table>
Risk Assessment

- $P_c$ and miss distance data alone cannot be used to fully assess the threat
  - The $P_c$ can be “high” even with large miss distances – this is typically due to very large position uncertainties.
    - Although mathematically “correct”, the $P_c$ is not necessarily representative of the collision threat
    - The decision to maneuver can be very difficult

- Close approach events are evaluated by analyzing:
  - Orbit determination (OD) consistency from solution to solution
    - Number of tracks and observations
    - Ballistic Coefficient
    - Solar Radiation Pressure Coefficient
    - Energy Dissipation Rate
    - Radar Cross Sectional Area
  - $P_c$ and $P_c$ sensitivity analysis
  - Conjunction Geometry (clock angle, approach angle)
  - Position of hard body radius with respect to the 3-sigma covariance ellipse
Risk Mitigation

- If the threat evaluation indicates the need to plan and (possibly) execute a maneuver:
  - Maneuver must sufficiently increase the separation distance and decrease the collision probability
  - Maneuver must meet orbit requirements if at all possible
- The maximum delta-V that will maintain control box requirements is obtained from the Flight Operations Team.
- Several maneuver options are generated and weighed against mission constraints
  - Vary the maneuver execution time with a fixed delta-V
  - Vary the delta-V for a fixed maneuver execution time
- Results are plotted; the best maneuver is chosen based on:
  - the successful mitigation of the conjunction
  - the minimum delta-v necessary
  - the effect on consecutive conjunctions with the same object

Sensitivity of $P_c$ to variations in burn performance is analyzed
Maneuver Planning Process

- Maneuver planning begins ~ TCA-3 days
  - As TCA approaches, uncertainty decreases, but avoidance options decrease
- Allows time to:
  - Improve the OD solution on the secondary object
  - Evaluate several maneuver options
  - Have 1st SPCS screen the options for post-maneuver close approaches
  - plan the final maneuver
  - Upload commands to the spacecraft
Operations Experiences

- Actions taken to date (1/05-2/07):
  - Aqua Ground Track Maintenance Maneuver waived off (5/05)
  - Terra Risk Mitigation Maneuver executed (10/05)
  - Aqua Ground Track Maintenance Maneuver waived off (12/05)
  - Terra Ground Track Maintenance Maneuver waived off (1/06)
  - TDRS Risk Mitigation Maneuver executed (1/06)
  - PARASOL Risk Mitigation Maneuver executed (1/07)
  - SAC-C Risk Mitigation Maneuver executed (2/07)

- Automation is essential for managing the workload of routine data processing
- Personnel experienced in orbit determination are required to assess the threat using multiple criteria
- Each event appears to be sufficiently unique such that a standardized mitigation approach cannot be adapted
- Each spacecraft sees a handful of conjunctions per year for which avoidance maneuver planning is considered
Earth Science Constellation

Conjunction Statistics
Average Number of Predicted Violations <1km per Asset per Month
New Objects per Month

Number of New Objects

0 20 40 60 80 100 120 140 160 180 200

Month

Nov-04 Dec-04 Jan-05 Feb-05 Mar-05 Apr-05 May-05 Jun-05 Jul-05 Aug-05 Sep-05 Oct-05 Nov-05 Dec-05 Jan-06 Feb-06 Mar-06 Apr-06 May-06 Jun-06 Jul-06 Aug-06 Sep-06 Oct-06 Nov-06 Dec-06 Jan-07 Feb-07

Landsat-7
Landsat-5 & Terra
SAC-C
EO-1
CloudSat & CALIPSO
Fengyun debris

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Apogee vs Perigee Height of Secondaries
Inclination Distribution of Secondaries

![Graph showing the distribution of inclinations](image)

**Inclination Bins (deg)**

- (0, 45) - 29
- (45, 65) - 33
- (65, 75) - 131
- (75, 85) - 87
- (85, 95) - 9
- (95, 99) - 170
- (99, 100) - 16
- (100, 180) - 5

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Fengyun 1C Debris Inclination Distribution

Number of Objects

Inclination Bins (deg)

[0,95) 22 72 437 406 [99.5,100) [100,101) [101,105) [105,180)
Conclusions

- Have successfully mitigated threats to NASA Robotic assets using our process and tools
- Looking forward to partnering with AFSPC to exchange access to the pertinent data for results of analysis studies which would be performed for mutual benefit to our organizations.