Making Debris Avoidance Decisions for ESMO’s EOS Mission Set

SSA Operator Conference - Denver, CO
November 3-5, 2016

Dimitrios Mantziaras, Terra Mission Director
Agenda

• Terra Mission Overview
• Orbital Constraints
• High Level Aspects of CA Process
• Notification Timelines
• Aura Close Approach → Creation of DAWG
• Process Improvements
  – Reduced Maneuver Execution Time
  – Identified Risk Thresholds
  – Identified Information Needed to make decision
  – Generated & Documented Process Flow
• Future Plans & Challenges
• Backup Slides
  – Role and Responsibilities
Terra Mission Overview

**Terra Features**
- **Launch Date:** December 18, 1999 (Atlas IIAS, VAFB)
- **Orbit:** 705 km, Sun-synchronous polar, 98.2° Inclination, 10:30 AM MLT descending node
- **Instrument Payload:**
  - ASTER (SWIR, TIR & VNIR) - Advanced Spaceborne Thermal Emission and Reflection Radiometer (Japan)
  - CERES (Fore & Aft) - Clouds and the Earth’s Radiant Energy System (USA – Langley)
  - MISR - Multi-angle Imaging Spectro-Radiometer (USA – JPL)
  - MODIS - Moderate Resolution Imaging Spectro-radiometer (USA – GSFC)
  - MOPITT - Measurement of Pollution in the Troposphere (Canada)
- **Project Management:** Earth Science Mission Operations (ESMO)
- **Spacecraft Flight Operations:** Contracted by GSFC to Honeywell / ASRC/JBS/AIMM team and supported by NASA NENs and TDRSS
- **Instrument Operations and Science Data processing:** Performed at respective Instrument Locations where developed
- **Mission Duration:** Successfully completed Prime mission of 5 years. Currently in Extended Operations.
- **Distributed Active Archive Centers:** LP DAAC – MODIS, ASTER; Langley DAAC – CERES, MISR, MOPITT

**Science**
- The primary objective of the Terra Mission is to simultaneously study clouds, water vapor, aerosol, trace gases, land surface and oceanic properties, as well as the interaction between them and their effect on the Earth’s energy budget and climate.
• The orbit is designed to maintain a nearly constant angle between the Ascending or Descending Node (AN/DN) and the Mean Sun
• This angle is measured in hours and is called the Mean Local Time (MLT)
• An MLT of 12:00 means the angle between the Node and Mean Sun is zero
• An MLT of <12:00 means the Node crossing appears to the west of the Mean Sun
• The Terra MLTDN control box is 10:29 – 10:31

• Luni-solar gravitational perturbations (from Sun and Moon) on an orbit cause the inclination to drift away from the ideal inclination
  – This causes the nodal rate to move away from the ideal 360°/year resulting in Mean Local Time drift.
  – Inclination maneuvers are periodically performed to maintain the nodal rate around the desired value in order to keep the MLT within limits
• An ideal semi-major axis (SMA) must be flown in order to fly the WRS-2 ground track.
EOS Mission Orbit Constraints

16 Day Repeat Cycle

- Flying at 705km sun-synchronous orbit provides the benefit of repeating the same exact ground track every 16 days
- Both the **Altitude** and **MLT/Inclination** have to be controlled to achieve this benefit
## Highly Level Aspects of CA Process

### Mission Director’s Perspective

<table>
<thead>
<tr>
<th>Information Source</th>
<th>Readiness for Action</th>
<th>Decision for Action</th>
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<tbody>
<tr>
<td><strong>Sensor data from JSpOC</strong></td>
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<tr>
<td>– Routine Screenings</td>
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<td>– Tasking Prioritization</td>
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<tr>
<td><strong>Data Analysis</strong></td>
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<tr>
<td>– Understanding confidence in solution</td>
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<td>– Assessing risk</td>
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<td>– Identifying burn times &amp; duration</td>
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<td><strong>Maneuver Planning</strong></td>
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<tr>
<td>– Contact Scheduling</td>
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<tr>
<td>– Product Generation &amp; Delivery</td>
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<td></td>
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<tr>
<td>• Ephems &amp; Planning Aids</td>
<td></td>
<td></td>
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<tr>
<td>– Coordination with Instrument Operations Team</td>
<td></td>
<td></td>
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<tr>
<td>– Identifying options within mission/science constraints</td>
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</tr>
<tr>
<td><strong>Maneuver Execution</strong></td>
<td></td>
<td></td>
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<tr>
<td>– Use propulsion system to impart delta-v on spacecraft</td>
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<td></td>
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<tr>
<td>– Returning to nominal science data collection state</td>
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</table>
Drag Make-Up -> Debris Avoidance Maneuver Concept

- EOS Missions fly in repeat ground track orbit at 705kms

- Spacecraft designed to perform Drag Make-Up (DMU) and Inclination Maneuvers
  - Retrograde capability not part of nominal maneuver set

- Drag Make-Up Maneuvers therefore used to mitigate debris risk
  - Raise altitude (can only go up, one direction)

- Differences in DMU & Debris Avoidance Maneuver (DAM) concepts are significant

<table>
<thead>
<tr>
<th></th>
<th>DMU</th>
<th>DAM</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Purpose</strong></td>
<td>Maintain Orbit Altitude</td>
<td>Avoid Debris</td>
</tr>
<tr>
<td><strong>Notification Time</strong></td>
<td>Several Weeks</td>
<td>Few Days or Less</td>
</tr>
<tr>
<td><strong>Ops Mentality</strong></td>
<td>Routine, Methodical</td>
<td>Urgent, Quick Turnaround</td>
</tr>
<tr>
<td><strong>Contingency Action</strong></td>
<td>Reschedule</td>
<td>Health &amp; Safety Concern</td>
</tr>
<tr>
<td><strong>Burn Duration</strong></td>
<td>Well Defined</td>
<td>Variable</td>
</tr>
<tr>
<td><strong>Burn Options</strong></td>
<td>One</td>
<td>Multiple</td>
</tr>
<tr>
<td><strong>Execution Time</strong></td>
<td>Day Shift Only, M-F</td>
<td>Anytime, Any Day</td>
</tr>
</tbody>
</table>
Generic Notification Timeline Scenarios (2008)

**Well Tracked, Early Notice Secondary Object**
(Stable Pc)

**Poorly Tracked, Late Notice Secondary Object**
(Variable Pc)

*Source: Brian Robinson, 2008*
Challenges Encountered

• Relatively short time frame to work the problem
  – Operational constraints that determine minimum turn-around time
• Spacecraft constraints that limit options
  – No retrograde maneuvers
  – Hadn’t performed short duration burn
• Orbit Maintenance Requirements that limit response
  – Need to stay in control box (small burns only)
• Coordination with Instrument Teams
  – Different time zones
  – Reconfiguration requests via stored commands
• Limited Resources

Lessons Learned

• Need to better understand/model performance of short maneuvers
• Uncertainty in the secondary object may lead to the desire to wait as long as you can before performing the maneuver, in order to get as many data points as possible
  – Forces turn-around time of planning/executing a maneuver to be very condensed
    • Need to analyze current processes/constraints to see if turn-around time can be shortened
• CA and FOT teams need to better understand each other’s processes
  – Need SOPs to define CARA & FOT processes for planning/executing DAMs
  – Need to define/better understand how CARA and FOT processes fit together
• Kicked Off Debris Avoidance Maneuver Working Group (Flight Dynamics, FOT & CARA)

CA Timeline

• Sat 6/21 – Close Approach predicted for 6/27 (30m, Pc of 1:13)
• Mon 6/23 – CARA briefed Mission Director (8am) and FOT (11am)
• Mon 6/23 – Aura Close Approach (CA) Kick-Off Meeting (4pm)
  – FDS/CARA recommends to initiate maneuver planning for TCA ~ 48hrs
• Tue 6/24 – CA/Debris Avoidance Maneuver (DAM) Meeting (9am)
  – 4 additional updates received since kick-off meeting
• Tue 6/24 – CA/DAM Status & Planning Meeting (4pm)
• Wed 6/25 – CA/DAM Status & Planning Meeting (9am)
• Wed 6/25 – CA/DAM Status & Planning Meeting (4pm) – CAM
  – Pc peaks at ~48% with minimum miss distance of ~11 meters
• Thu 6/26 – CA/DAM Status & Planning Meeting (7am)
• Thu 6/26 – FOT performs DAM at 10:25am (2-second burn)
• Fri 6/27 – Predicted Time of Close Approach (TCA) was 11:34am

• 6 meetings to discuss conjunction
• Pc peaked at ~48% with miss of ~11m
• Early burn planned (24-48 hours prior to TCA)

Aura Close Approach Summary
June 2008 (DAM)
Shortening DMU Timescale for DAMs

**Original DMU Timing**

- Process started ~2 weeks before maneuver
- Main prep activities ~2-3 days prior to maneuver
- Multiple personnel required
- Reliant on stored commands

**Accelerated DMU Timing**

- Process shortened to begin the day before the maneuver
- Main prep activities 1 day prior to maneuver
- Reduced personnel required
- Reliant on stored commands
## Risk Thresholds at Decision Point

### ESC Maneuver Thresholds for DAM/No-DAM

<table>
<thead>
<tr>
<th>Pc Thresholds</th>
<th>Odds Range</th>
<th>Course of Action</th>
<th>Sample Scenarios</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Green</strong></td>
<td>$&lt;1.0\times10^{-5}$</td>
<td>1:100,000 to 0</td>
<td>No DAM</td>
</tr>
<tr>
<td><strong>Yellow</strong></td>
<td>$(1.0\times10^{-4}-1.0\times10^{-5})$</td>
<td>1:10,000 to 1:100,000</td>
<td>Altered DMU/No DAM • Maneuver of convenience; Replan Nominal DMU burn time or execute DMU early • For well-tracked objects with small miss distances</td>
</tr>
<tr>
<td><strong>Orange</strong></td>
<td>$(1.0\times10^{-3}-1.0\times10^{-4})$</td>
<td>1:1,000 to 1:10,000</td>
<td>DAM Solution within mission/science requirements and low uncertainties</td>
</tr>
<tr>
<td><strong>Red</strong></td>
<td>$(1.0\times10^{-2}-1.0\times10^{-3})$</td>
<td>1:100 to 1:1,000</td>
<td>DAM Execute even if outside mission/science requirements</td>
</tr>
<tr>
<td><strong>Black</strong></td>
<td>$\geq1.0\times10^{-2}$</td>
<td>1:100</td>
<td>DAM Maneuver at all costs Even if Ongoing (Non-Maneuver Component) Anomaly or Unscreened Maneuver</td>
</tr>
</tbody>
</table>

- All unacceptable risks are mitigated
- Additional risks are mitigated with mission/science constraints
- Confidence in OD solution/risk accuracy must be considered as well
Information Needed to Make Decision

### Info Needed for All Objects (Each Update)

- Days to TCA
- TCA
- Secondary Object Name & Catalog Number
- Primary Object Ephem Source (ASW or O/O)
- Screening Epoch
- Total Miss Distance (m)
- Miss Components (R, I, C – meters)
- Pc (single object & aggregate for mission)
  - Color coded to visual help identify risk categories
    - Red, Yellow, Green, Orange & Black
    - Thresholds for each category set by ESMO by Mission
- Indication if New Track received on Secondary
- Relative Velocity/Approach Angle
- Indication if Active Mission

### Info Needed for High Interest Objects

- Repeat of summary info for object in question (info on left)
- Plots of Total Miss History, Pc history, Component Uncertainty History
  - Indicate which data points contained a new track
- Ephem name used for O/O solution
- Event Geometry (in table form – both ASW and O/O columns)
  - Component Uncertainties
  - Relative Velocity
  - Approach Angle
- Secondary OD info
  - Orbital Parameter (Period, Perigee Height, Apogee Height, Inclination, EDR & RCS)
  - Avg. Observations per day
  - OD Fit Span (days)
  - Time Since Last Observation
  - Total Propagation Time (days)
  - Orbital Parameter & Event Flag Info
  - Space Weather Info
  - How well behaved is the secondary object??
- Maneuver Trade Space Plots
  - Combined, Secondary, Post-Maneuver Objects of Concern
  - Timeframe of MTS plot would be dictated by Event Type/Mitigation Approach
  - Delta-V or Burn Duration to stay within Mission/Science Control Box
- Optimized Maneuver Solution (show on plot & separate)
  - Targeted probability for maneuver solution mitigating risk
• Reviewed Overall Process with Mission Stakeholders
• Documented the Overall CA Process in the Mission Director Handbook
Maneuver Execution Enhancement

- **Needed to remove reliance on Stored Commands (ATC)**
- **TMON/RTCS enhancement**
  - Upload time of burn
  - Upload burn duration
- **TMON will wait to run until time uplinked then kick-off RTCSs**
- **Still need to generate ephem, get it screened and evaluate results**
- **Timeframe and how it improved**
  - ATC need by 1500-1900z day before
  - TMON patched by 4 hours prior to burn

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### To be Executed Via TMON Process on 2016 / 105

<table>
<thead>
<tr>
<th>RTCS/RTCS</th>
<th>GMT Time</th>
<th>To be Executed Via TMON Process on 2016 / 105</th>
<th>Rel CMD Timing</th>
</tr>
</thead>
<tbody>
<tr>
<td>TMON 55</td>
<td>13:15:38</td>
<td>TMON 55 Activation</td>
<td>(DV - 1:00:01)</td>
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<tr>
<td>RTCS 30</td>
<td>13:15:39</td>
<td>OK/ Master RTCS 30 Activated</td>
<td>(DV - 1:00:00)</td>
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<tr>
<td>RTCS 180</td>
<td>13:30:39</td>
<td>FS1, DISABLE NPSH PLT</td>
<td>(DV - 0:45:00)</td>
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<tr>
<td></td>
<td>13:30:49</td>
<td>TCS, DISABLE TANK, HIA</td>
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<tr>
<td></td>
<td>13:30:41</td>
<td>FS1, DISABLE WSPD CTL</td>
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<td></td>
<td>13:30:45</td>
<td>GNC, SET_RRA, HRAKE</td>
<td>0:00:28</td>
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<td>13:30:49</td>
<td>GNC, SET_IRAD, HRADE</td>
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<td></td>
<td>13:53:59</td>
<td>CEA, SET IC, SEQHOLD</td>
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<tr>
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<td>13:54:49</td>
<td>CEF, SET IC, APOS SP1, SP2</td>
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<td>13:56:11</td>
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<td>USE, NOM ORB RATE</td>
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<td>FS1, DISABLE SC, FF</td>
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<td>FS1, SELECT HGA, EPA</td>
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<td>FS1, SET INHIBID(18)</td>
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<td>PMS, ARM REALI800000</td>
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<td>FS1, SELECT DA, MODE</td>
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<td>14:10:45</td>
<td>TCS, DISABLE CHKTIBTA</td>
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<td>1:38:58</td>
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<td>15:55:39</td>
<td>CEA, SET IC, SEQCTRK</td>
<td>1:38:58</td>
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</tbody>
</table>
Updated ESMO CA Process Flow - 2016

Identification
- Wait for Update
  - OSAs posts new CDM/VCM on SpaceTrack
  - No: TCA < 5 days and $P_c > 1e-5$
    - No: TCA < 3 days and $P_c > 1e-5$
    - Yes: HIE Identified
      - Generate Text Message Alert
        - ESMO
  - Yes: HIE Identified
    - FDS generates Burn Ephems for each option
    - CARA sends options to JSpOC
    - OSAs screen ephems and post results to SpaceTrack
    - Generate screening results report
    - ESMO evaluates options
      - Yes: Options mitigate Risk?
        - No: Select New Maneuver Option(s)
          - CRMS Maneuver Report
        - Yes: Manually Generate Ephems
          - CRMS Maneuver/HIE Report
    - CARA performs analysis of maneuver options (Generates HIE report/CAM materials)
      - If necessary, Conduct Go-CAM Burn - 3 hours
        - Go
          - Execute Maneuver
          - Inform Science & Neighbors
      - Select Maneuver Option
        - No-Go
          - Deliver/Upload No Burn Products
        - Waive-Off
          - No
            - Conduct CAM Burn - 18 hours
            - Burn?
              - No
Future Enhancements/Challenges

**Enhancements**

- **Maneuver Planning Automation**
  - Multiple Conjunction Considerations
  - Move toward Cumulative Pc versus individual object Pc
  - Working towards pre-canned maneuver avoidance plans with associated ephems built autonomously each day for all HIEs
  - Ephems would be delivered to CARA/JSpOC for screening and results would be interpreted and sent out in a report autonomously for evaluation
  - Move towards decisions & workload confined to TCA – 24 hours or less

**Challenges**

- **Space Fence**
  - What will order of magnitude increase looks like in terms of workload?
  - How many objects that are single station tracked?
  - Will we be able to believe data enough to make maneuver decisions on?
  - What will evaluation/decision workload look like in that environment?
  - More collisions/debris
  - Post maneuver concerns shortly after burn solutions
Questions??
BACKUP SLIDES
High Level Roles and Responsibilities

CARA Orbital Safety Analyst (OSA) @ JSpOC Responsibilities:
• Post CDM/VCMs to SpaceTrack (reg update, 1v1s or screening results)
• Perform screenings
• Perform manual OD adjustments as required
• Adjudicate tasking levels for catalog objects

NASA CARA Analyst Responsibilities:
• Investigate Conjunctions that are high risk or have space weather concerns
  ➢ Request elevated tasking or 1v1s as appropriate
• Communicate risk to mission management
• Analyze High Risk Conjunctions & associated maneuver options (as requested)
• Develop High Interest Event (HIE) Briefings
• Support Maneuver Command Authorization Meetings (CAMs)

Space Track (Air Force managed):
• Interface to Data (requires login)

ESMO Flight Dynamics Responsibilities:
• Provides delta-v buffers
• Maneuver Planning (Generate & Deliver Ephemerides)

ESMO Collision Risk Management System (CRMS) responsibilities (developed by SpaceNav):
• Automated conjunction risk reduction balancing Collision Risk and Mission Requirements
  ➢ Generate maneuver options & associated reports