2018 Space Situational Awareness OPERATORS’ WORKSHOP

November 13-16, 2018

To Maneuver or Not to Maneuver That is the Question

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Topics

- Beginning of ESMO Operational Collision Avoidance
- Early Earth Observing System (EOS) Debris Avoidance Maneuvers (DAMs)
- Recent EOS Aqua Challenging Case Studies
- EOS High-Interest Events (HIEs) Statistics
- EOS Observations and Challenges
- Questions
March 2002: NASA/GSFC Orbital Debris Workshop:

- NASA Policy to Limit Orbital Debris Generation
- Case Studies:
  - CGRO Controlled Reentry (May-June 2000)
  - Landsat-4 Decommissioning (May-June 2001)
  - TRMM Orbit Raise (August 2001)
- Landsat-7 Conjunction Assessment Study (January 2002)
  - Multiple conjunctions per day
  - Began working to establish procedures for ongoing support to ESMO EOS missions
Early Days
Aqua and Aura Maneuver Screenings

• May 2002: Screened Aqua Ascent Maneuvers
• October 2003: Screened Aqua Inclination Adjust Maneuver (IAM) #1
• March 2004: Screened Aqua IAM #2
• May 2004: NASA request to US Department of Defense to establish routine conjunction assessment process for NASA robotic missions
• July 2004: Screened Aura Ascent Maneuvers
• Fall 2004: Screened Aqua & Aura IAMs

NASA/GSFC Goals

- NASA/GSFC would like to establish an interface with USSTRATCOM for routine conjunction assessment screening of high importance NASA/GSFC assets
- Desire a simple (JSC-like) interface between NASA/GSFC and Cheyenne Mountain Operations Center (CMOC)
- 7-day-a-week, automated operation, supplemented by 24x7 around-the-clock mission operations personnel
- Automatic notification within 24-hours of any close approach that would require an evasive maneuver
- Probabilistic determination of need to maneuver (JSC-like)
- Documented in an Operations Agreement between GSFC & USSTRATCOM
  - Appendix for each Program supported e.g. EOS, TDRSS, TBD
### Routine Conjunction Assessment
#### 2005 Screening Build-up

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11/15/2018
Early EOS Debris Avoidance Maneuvers
EOS Terra vs. 14222
(SCOUT G-1 Debris)

- **1st NASA Robotic Mission Debris Avoidance Maneuver (DAM)**
  - October 21, 2005
  - Maximum Pc of 8.2E-02 (about 1:12)
  - Minimum miss distance about 37 meters
  - Mitigated by 2.7 second mini-drag make-up maneuver (#44 for the mission)
  - Burn at TCA minus 48-hours
  - Miss Distance based Max Pc approach
  - Miss Distance → about 4.5 km
  - By performing a maneuver that increases the miss distance to 4km, the maximum collision probability was reduced to below 1E-04 (1 in 10,000)

Reference: Lauri Newman and Matt Duncan, AIAA 2006-6291
Collison Avoidance Maneuver Performed by NASA’s Terra Spacecraft

The Terra spacecraft, often referred to as the flagship of NASA’s Earth Observing System (EOS), successfully performed a small collision avoidance maneuver on 21 October 2005 to ensure safe passage by a piece of orbital debris two days later. This action demonstrated the effectiveness of a conjunction assessment procedure implemented in 2004 by personnel of the NASA Goddard Space Flight Center (GSFC) and the U.S. Space Surveillance Network (SSN). The trajectories of Terra and its companion EOS spacecraft are frequently compared with the orbits of thousands of objects tracked by the SSN to determine if an accidental collision is possible. More than 2600 objects are known to pass through the altitude regime of Terra multiple times (sometimes more than two dozen) each day.

Terra (International Designator 1999-068A, U.S. Satellite Number 25994) was launched on 18 December 1999 on a nominal 6-year mission to monitor the complex nature of the Earth’s atmosphere and surface. The nearly five-meter-tall spacecraft circles the Earth at an altitude of 705 km with an orbital inclination of 98.2°. When a conjunction assessment on 17 October predicted a piece of debris from a Scout G-I upper stage (International Designator 1983-063C, U.S. Satellite Number 14222) would come within 300 m of Terra on 23 October, GSFC and SSN personnel undertook a more detailed assessment of the upcoming conjunction.

The Scout debris was in an orbit with an altitude similar to that of Terra (approximately 680 km by 710 km), but its postlaunch inclination of 82.4° and different orbit plane meant that a collision would have occurred at a high velocity of nearly 12 km/s. By 21 October, refined analysis of the future close approach indicated that the miss distance was only approximately 50 m with an uncertainty that yielded a probability of collision on the order of 1 in 100. Consequently, a decision was made for Terra to execute a collision avoidance maneuver.

Terra normally maneuvers a few times each year to maintain its precision orbit, and the collision avoidance maneuver was designed to serve this same function to prevent the waste of precious propellant. A very small maneuver was performed nearly two days before the anticipated encounter, ensuring that the Scout debris would pass Terra at a distance of more than 4 km. A post-encounter assessment confirmed that this goal was achieved without disruption to the important Terra mission.
EOS Terra vs 31410
(Fengyun-1C Debris)

- **2nd EOS Terra DAM**
  - June 22, 2007
  - Maximum Pc of 1.6E-01 (about 1:6)
  - Minimum miss distance about 18 meters
  - Mitigated by 1.35 second maneuver (#50)
  - Burn at TCA minus 24-hours
  - Miss Distance based approach
  - Miss distance → about 1.2 km
  - Actual post-maneuver data showed that the resulting miss distance with the FENGYUN debris object was 1.227 km.

- **1st NASA Robotic Mission DAM to Avoid Debris Caused by Chinese A-Sat Test (January 2007)**

Reference: GSFC Flight Dynamics Task Order 209 Technical Memorandum 209-091
Made the Front Page of NASA News on 11/15/2018
The large number of debris from Fengyun-1C are posing greater collision risks for spacecraft operating in low Earth orbit. The number of close approaches has risen significantly. On 22 June, NASA’s Terra spacecraft had to execute a collision avoidance maneuver to evade a fragment from Fengyun-1C that was on a trajectory which would have passed within 19 meters of Terra.
EOS Aura vs. 01399
(TRIAD 1 Debris)

- **1st EOS Aura DAM**
  - June 26, 2008
  - Maximum Pc of 4.8-E-01 (about 1:2)
  - Minimum miss distance about 11 meters
    - half the size of Aura
  - Mitigated by 2.0 second (0.9 cm/sec) maneuver (#15 for the mission)
  - Burn at TCA minus 24-hours
  - Miss Distance based approach
  - Miss distance → about 500 meters
  - Miss distance needed to mitigate conjunction beyond 3-sigma combined covariance was about 150 meters

Jump forward 10-Years

Recent EOS Aqua Challenging Case Studies
ESMO Collision Risk Management (CRM) process currently being supported by two systems
- NASA Conjunction Assessment and Risk Analysis (CARA) Team
- SpaceNav Collision Risk Management System (CRMS)

ESMO and CARA are working together to Devolve CARA Conjunction Analysis (CA) operations capabilities into the EOS Control Center
- ESMO to transition exclusively to CRMS
- ESMO currently in Pilot Program with CARA

Some recent challenging High Interest Events (HIEs)
- Aqua vs. 35917: TCA on 12/5/2017 at 05:27:59 GMT (Case Study #1)
- Aqua vs. 37593: TCA on 7/12/2018 at 04:02:37 GMT (Case Study #2)
Case Study #1

Aqua vs. 35917
IRIDIUM-33 DEBRIS
TCA: 2017-12-05 at 05:27:59 GMT
High Interest Event (HIE) Conjunction

- 2.3-days to TCA (late/short notice?)
- TCA: 2017-12-05 at 05:27:59 GMT
- ASW Pc of about 1:859 (1.16E-3)
- ASW miss distance about 719 meters
  - Radial (R) = 108.7m
  - In-Track (I) = -504.5m
  - Cross-Track (C) = 501.2m
- Poorly tracked secondary (0.4 tracks/day)
  - Last Tracked 12/2 at 21:30z
  - 13.5 day OD Fit Span
- Tracked by a Single Station
- Relatively large RIC uncertainties
- Why the additional miss distance points?

Credit: NASA Conjunction Assessment and Risk Analysis (CARA) Team
EOS Aqua vs. 35917
(Case Study #1)

- **CRMS Maneuver Planning (Manual)**
  - Small maneuver Delta-V Budgets
    - Center = 3.59 cm/sec
    - -10 km = 4.89 cm/sec
    - -20 km = 5.80 cm/sec
  - Manually generated maneuver options
  - Repeated process on Sunday and Monday
  - Generated and screened 7 maneuvers
    - Options 1-3: = above sizes
    - Option 4: = 10.0 cm/sec
    - Options 5-7: = 2.46, 7.0 & 13.78 cm/sec
  - Even looked at retrograde maneuvers
  - Predicted mild geomagnetic storm (G2)
  - CARA High Interest Event (HIE) Briefing
• No tracking for about 2-days?
  – 0.25-days to TCA (about 6-hours)
  – Single track by a single station
  – ASW Pc of about 1:982 (1.02E-3)
  – ASW miss distance about 960 meters
    » Radial = 106.9m +/- 110.5m
    » In-Track = -671.8m +/- 1175.6m
    » Cross-Track = 673.0m +/- 352.1m
  – 7 maneuver options screened
    » Large enough maneuver to mitigate the risk will cause Aqua to exit its orbit science requirements for months
  – Final CARA HIE Briefing
  – Command Authorization Meeting (CAM)

• To maneuver or not to maneuver?
• Final Decision at TCA minus 5.5-hours (12/5 at 0000z)
  – CARA confirmed we passed last tracking opportunity with no new tracks on the secondary
  – Based on poor OD quality, determined the best course of action was to monitor the conjunction through TCA and take no action

• Notified NASA HQ and GSFC Management at TCA-4hr
  – Scheduled a real-time contact thru TCA to monitor the spacecraft

• Every HIE is a learning opportunity – Questions:
  – Was the poorly tracked high-risk/small miss distance HIE Actionable
  – OD accuracy of single station tracked secondary object
  – What’s a sufficient post-maneuver Pc to “drive to”

• Hindsight is always 20-20 (See Case Study #2)
Case Study #2

Aqua vs. 37593
FENGYUN-1C DEBRIS
TCA: 2018-07-12 at 04:02:37 GMT
• A Challenging (?) High Interest Event (HIE) Conjunction
  – TCA: 2018-07-12 at 04:02:37 GMT – middle of the work week
  – ASW Maximum Pc of about 1:158 (6.32E-3)
  – ASW Minimum Miss Distance about 70.3 meters
    » Radial (R), In-Track (I), Cross-Track (C) = 69.8m, 0.6m, -8.4m
  – Poorly tracked secondary
    » One track every 1.3 days (0.78 tracks/day)
    » Tracked by a single station
    » ~17-day Orbit Determination (OD) Fit Span
  – RIC uncertainties
    » CARA = 58.8m, 1573.7m, 518.4m (in conjunction plane)
    » CRMS = 61m, 1604m, 24m (in body frame at TCA minus 6.9-days)
  – Increased tasking requested and received
  – Followed for entire 7-day screening period

EOS Aqua vs. 37593
FENGYUN-1C DEB
SUMMARY

Credit: NASA Conjunction Assessment and Risk Analysis (CARA) Team 11/15/2018
EOS Aqua vs. 37593
(Friday July 6th at 16:22 GMT: TCA minus 5.5-days)

- No tracking for about 2 days
  - High-Risk/Low Miss Distance HIE
  - Tracked by a single station (0.7/day)
  - OD Fit Span of about 17-days
  - Last Tracked on 7/4 at 12:20 GMT
  - ASW Pc of about 1:275 (3.64E-3)
  - ASW Total Miss Distance about 112.7 meters
    » Radial (R), In-Track (I), Cross-Track (C) = 87.8m, 6.9m, -70.3m

- MD Assessment: Ample time to work the conjunction starting Monday morning – TCA is Wednesday evening local (Thursday 7/12 GMT day at 04:02:37 GMT)
  - CRMS automatically starts generating maneuver options at TCA-3 days (AutoRMMs) if secondary has been tracked in last 48-hours
• Overnight CARA Screening Report
  – No new tracking on secondary (4.8-days)
  – ASW Pc of 1:194 (5.16E-3)
  – ASW miss distance of 80.2 meters

• CRMS Maneuver Planning
  – 1st CRMS Maneuver Trade Space manually generated Monday afternoon around 2pm
  – Small RMM/DAM Delta-V Budgets
    » Center, -10km, -20km about 2, 3, 4 cm/sec
  – Mitigation near TCA requires a larger maneuver than RMM/DAM Delta-V Budget
  – Obvious benefit to performing early DAM
  – WAITING ON A NEW TRACK

• 3:25pm EDT: CARA Notification – Requests Timeline
EOS Aqua vs. 37593
(Monday Afternoon July 9th from CARA Debrief)

- **CARA Assessment: 9 July Afternoon Screening:**
  - Still no new tracking obtained; now 5 days since last track
  - Given average of about 1 track every two days, this is unexpected. However, the secondary was tasked at the highest level and single station tracked causing limited ability to further address the situation

- **No ephemerides delivered via Aqua's automated RMM generation as expected**
  - CARA routinely process RMM ephems from CRMS for high Pc events

- **CARA sent initial notification email to the mission following standard process – Requests Timeline**
  - If the event was deemed inactionable, this would have been stated in the notification email (IMPORTANT FACTOR about ASSUMPTIONS)

- **Nominally, events identified as RED will require a mitigation maneuver**
CRMS Manual Maneuver Planning
- CRMS not generating AutoRMMs *(stale data)*
- Small RMM/DAM Delta-V Budgets
  » Center, -10km, -20km about 2, 3, 4 cm/sec
- Manually Generated/Screened 0 maneuvers
  » None were generated on Tuesday

Significant internal (ESMO) discussion concerning the actionability of the conjunction (Secondary not tracked for 6-days)

MD/ESMO Assessment: (2pm email to CARA)
- CRMS/FOT CAE monitoring the conjunction
- MD requested tracking opportunities to TCA ➔
- Will provide maneuver options tomorrow

EOS Aqua vs. 37593
(Tuesday July 10th at 17:02 GMT: TCA minus 1.5-days)
EOS Aqua vs. 37593
(Wednesday July 11\textsuperscript{th} Morning thru early Afternoon)

- **No new tracking overnight 0.5-days to TCA**
  - 2 maneuver options generated and screened mid-day
    - 6.8 cm/s on 7/11 at 20:40 GMT (drive to E-7 level)
    - 8.5 cm/s on 7/12 at 03:12 GMT (drive to E-7 level)
    - Large enough maneuver to mitigate the risk will cause Aqua to exit its orbit science requirements for months (No retro-grade maneuver capability)
  - 2 maneuver options generated and screened during the early afternoon in anticipation of a potential track and reduction in the uncertainties but high enough risk to require maneuvering
    - 3.0 cm/s on 7/12 at 03:12 GMT
    - 4.0 cm/s on 7/12 at 03:12 GMT

- **1:05pm EDT – MD/ESMO Assessment: Non-actionable**
  - Schedule 4:30pm EDT ESMO/CARA Meeting
  - Request tracking history
Secondary Orbit Determination (OD) Discussion:
- Secondary last tracked on 7/4 about 7-days ago
- Object is not lost per discussion with CARA OSAs
- OD Span contains 13 tracks over 17 days
- OD Span is 17 days; EDR is 1E-4, At this EDR, OD Span is reasonable
- Given OD Span, time since last track not expected to degrade solution to inactionability
- Rule of Thumb: time since last track should not be longer than the LUPI (OD Span)

Actionability Recommendation:
- CARA Operations and Analysis teams in agreement that this event is actionable

Summary & Recommendations:
- CARA considers this HIE actionable
- Recommends executing 8.5cm/sec DAM
• Command Authorization Meeting (CAM)
  – TCA in about 9-hours at the CAM
  – No tracking for 7+ days
  – Single track by a single station
  – ASW Pc of 1:192 (5.22E-3) at TCA-0.5\textsuperscript{d}
  – ASW miss distance of 80.6 meters at TCA-0.5\textsuperscript{d}
    » Radial = 75.7m +/- 58m
    » In-Track = 5.2m +/- 1626m
    » Cross-Track = -27.2m +/- 23m
  – Reviewed 4 maneuver options screened earlier
    » 6.8 cm/s, 8.5 cm/s, 3.0 cm/s and 4.0 cm/s
  – Reviewed 3 new maneuver options from HIEB
    » 5.5cm/s, 6.5 cm/s and 7.5cm/s

• To maneuver or not to maneuver?
EOS Aqua vs. 37593
(Wednesday July 11th Evening Post-CAM)

• Final Decision at TCA minus 4.5-hours (7/11 at 23:30z)
  – Execute 6.5 cm/sec DAM on 7/12 at 01:34:00 GMT (TCA – 2.5 hours)
  – CARA confirmed we passed last tracking opportunity with no new tracks on the secondary

• ESMO Notified NASA HQ and GSFC Management
  – Maneuver to be executed in the blind
  – Ground station contact about 15-minutes after the maneuver

• MD Notified ESC/A-Train Member Missions

• Every HIE is a learning opportunity – Some Questions
  – Was the poorly tracked high-risk/small miss distance HIE **Actionable**
  – OD accuracy of single station tracked secondary object
  – What’s a sufficient post-maneuver Pc to “drive to”

• What have we learned
EOS
High Interest Events
Statistics
# EOS Debris Avoidance Maneuvers (2005 – 2018-08-30)

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<td>19 Aug 2013 07:43</td>
<td>79</td>
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<td>15</td>
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<td>17</td>
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<td>19</td>
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<td>10 Feb 2014</td>
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<td>20</td>
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<td>9040</td>
<td>Delta 1 Debris</td>
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<td>21</td>
<td>Aura</td>
<td>36712</td>
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<td>29 Aug 2014</td>
<td>02 Sep 2014 12:32</td>
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<tr>
<td>23</td>
<td>Terra</td>
<td>35925</td>
<td>Iridium 33 Debris</td>
<td>31 Dec 2014</td>
<td>01 Jan 2015 06:24</td>
<td>206</td>
<td>9.67E-04</td>
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# EOS Debris Avoidance Maneuvers (2015 – 2018-08-30)

<table>
<thead>
<tr>
<th>Maneuver Number</th>
<th>Primary Object</th>
<th>Secondary Object Number</th>
<th>Secondary Object Description</th>
<th>Maneuver Date</th>
<th>TCA (GMT)</th>
<th>Minimum Miss Distance Observed [m]</th>
<th>Maximum Pc Observed</th>
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<tr>
<td>25</td>
<td>Terra</td>
<td>87692</td>
<td>AnalystSat</td>
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<td>16 Jun 2015 08:33</td>
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<td>34215</td>
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<td>26</td>
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<td>34726</td>
<td>COSMOS 2251 Deb</td>
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<td>28</td>
<td>Aura</td>
<td>25759</td>
<td>PSLV R/B</td>
<td>26 Mar 2017</td>
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<td>29</td>
<td>Terra</td>
<td>35627</td>
<td>IRIDIUM 33 Deb</td>
<td>06 Jul 2017</td>
<td>06 Jul 2017 04:26</td>
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<td>30</td>
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<td>33666</td>
<td>FENGYUN 1C Deb</td>
<td>16 Mar 2018</td>
<td>16 Mar 2018 17:35</td>
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<td>31</td>
<td>Aqua</td>
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### DAMs Re-plans

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<tr>
<th>DAMs Re-plans</th>
<th>Terra 25994</th>
<th>Aqua 27424</th>
<th>Aura 28376</th>
<th>Total</th>
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<tr>
<td>TOTAL DAMS</td>
<td>14</td>
<td>10</td>
<td>8</td>
<td>32</td>
</tr>
<tr>
<td>Postponed and or re-planned Maneuvers</td>
<td>6</td>
<td>15</td>
<td>16</td>
<td>37</td>
</tr>
</tbody>
</table>
EOS Observations and Challenges
EOS Observations

• Risk of an on-orbit collision between an operational mission and a piece of orbital debris is increasing

• Things will get worse before they get better

• Close approaches occur all the time

• Need to be able to plan and execute on short notice

– Mission Operations Paradigm Shift –
From monitoring Mission Health and Safety to Mission Protection & Preservation of Orbital Environment

- - - A risk to one is a risk to all - - -
EOS Challenges

- Relatively short time frame to work the predicted close approaches
  - Dynamically changing
  - Often considerable uncertainties

- Spacecraft Constraints limit options
  - No retrograde maneuvers during science mission

- Mission Orbit Maintenance and Constellation Flying Requirements that limit response options

- Operational Constraints that determine minimum turn-around time

- Limited Resources
You know you’re a Space Fence Junkie – IF

1. You pointed out all the inconsistencies in the movie Gravity... the first time you watched it.

2. You knew Pluto wasn’t a planet the first time you saw a drawing of the Solar System... in kindergarten.

3. When you’re stargazing with your friends, they ask you to name the constellations because you’re more accurate than their Sky Map app.

4. You named your dog Hubble.

5. In Boy Scouts/Girl Scouts, you earned your first badge from the NASA Orbital Debris Program Office.

6. You’ve scheduled your honeymoon in the Kwajalein Atoll in the Marshall Islands to coincide with the installation of the first Space Fence radar.

7. You have a painting on your living room wall of astronaut Ed White’s glove, the one he dropped while outside Gemini 4 in 1965, and that remained in orbit for a month. You lost a bid for his other glove on eBay.

8. You’re a big Tyson fan... not Mike. Neil deGrasse.

9. Your bedroom is modeled after the interior of the International Space Station.

10. You know Space Fence isn’t really a fence.
Thank you for your time and attention

Questions
<table>
<thead>
<tr>
<th>Abbreviations/Acronyms List</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-Sat – Anti-Satellite</td>
</tr>
<tr>
<td>ASW – Astrodynamics Workstation</td>
</tr>
<tr>
<td>CA – Conjunction Assessment</td>
</tr>
<tr>
<td>CAE – FOT Collision Avoidance Engineer</td>
</tr>
<tr>
<td>CAM – Command Authorization Meeting</td>
</tr>
<tr>
<td>CARA – Conjunction Assessment Risk Analysis</td>
</tr>
<tr>
<td>CGRO – Compton Gamma Ray Observatory</td>
</tr>
<tr>
<td>CMOC – Cheyenne Mountain Complex</td>
</tr>
<tr>
<td>CRMS – Collision Risk Management System</td>
</tr>
<tr>
<td>DAM – Debris Avoidance Maneuver</td>
</tr>
<tr>
<td>DMUM – Drag Make-up Maneuver</td>
</tr>
<tr>
<td>EDT – Eastern Daylight Time</td>
</tr>
<tr>
<td>EDR – Energy Dissipation Rate</td>
</tr>
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<td>EO-1 – Earth Observing-1 Satellite</td>
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<tr>
<td>EOS – Earth Observing System</td>
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<tr>
<td>ESC – Earth Science Constellation</td>
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<tr>
<td>ESMO – Earth Science Mission Operations</td>
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11/15/2018