Operational Collision Avoidance

Bill Guit/NASA/GSFC
Topics

• Early Days
• EOS Debris Avoidance Maneuvers
• EOS High-Interest Events Statistics
• A-Train Systematic Conjunctions
  – Landsat-5 Crossing A-Train
  – CloudSat Under-flight of Aqua
  – SAC-C Crossing A-Train
• Future Challenges
We do not inherit the Earth from our ancestors, we borrow it from our children

- Native American Proverb
- Haida Indian Saying
Over the 50-year development of the global space program – all spacefaring nations have contributed to the growing challenge of potential collisions between operational missions and orbital debris.
Early Days
NASA/GSFC Orbital Debris Workshop (March 2002)

- 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
  - Begin working to establish procedures for ongoing support
The Good, the Bad and the Ugly
(Who to credit – or blame depending on your perspective)

• **Good: CGRO De-orbit & TRMM Re-boost**
  - Well coordinated from and interagency perspective
  - DOD/NASA (GSFC and JSC/HSF)

• **Bad: Landsat-4**
  - Not well coordinated at an interagency level
  - Flipped spacecraft over and depleted the propellant

• **Ugly: EP/EUVE Reentry**
  - Couldn’t then/can’t now predict the date, time and location of reentry with any real accuracy
    -METRIC: Average error at T minus 2-hours is +/- 26-minutes
  - Uncontrolled reentry over the mid-east in January 2002
  - Midnight notification of Presidential Chief of Staff
Screened ascent maneuvers for EOS Aqua
Aqua Launch Control Room

The Far Side®
LAST IMPRESSIONS
2002

May

"Hey! What's that clown think he's doing?"
Early Days – 2004
(EOS Aura and PARASOL launches)

# Routine Conjunction Assessment

## 2005 Screening Build-up

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Early EOS Conjunction Assessment Experience (2005 – CARA began logging HIEs in May)

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<td>03927</td>
<td>12-May-05</td>
<td>Waived-off planned 5/11 routine drag make-up maneuver</td>
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<tr>
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<td>18665</td>
<td>17-May-05</td>
<td>Repeating CAs (6), additional CAs with 82095 and 87331</td>
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<td>25-May-05</td>
<td>Repeating CAs, near co-planar, low relative velocity CAs</td>
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<td>4579</td>
<td>06-Jun-05</td>
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<td>First NASA Robotic Mission Debris Avoidance Maneuver (DAM)</td>
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<td>24097</td>
<td>06-Dec-05</td>
<td>Waived-off planned routine drag make-up maneuver</td>
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</table>

Terra (5), Aqua (9), Aura (6) – TOTAL 20

CREDIT: NASA Robotic Mission CARA Team
Early Conjunction Assessment Statistics (First half of 2005)

About 11 conjunctions per week per mission

CREDIT: NASA Robotic Mission CARA Team
EOS
Debris Avoidance Maneuvers
EOS Terra vs. 14222 (SCOUT G-1 Debris) Debris Avoidance Maneuver

- 1st NASA Robotic Mission Debris Avoidance Maneuver (DAM)
  - October 21, 2005
  - Peak Pc of about 1:12
  - Minimum miss distance about 37 meters
  - Mitigated by 2.7 second mini-drag make-up maneuver
  - Burn at TCA minus 48-hours
  - Miss Distance → about 4.5 km
  - Pc → 0

Reference: Lauri Newman and Matt Duncan, AIAA 2006-6291
Collision 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-sphere 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-1 upper stage (International Designator 1983-063C, U.S. Satellite Number 14222) would come within 500 m of Terra on 23 October, GSFC and SSN personnel undertook a more detailed assessment of the coming conjunction.

The Scout debris was in an orbit with an altitude similar to that of Terra (approximately 680 km by 710 km), but its postgrade 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.
### Early EOS Conjunction Assessment Experience (2006 and 2007)

<table>
<thead>
<tr>
<th>Primary</th>
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**Terra (5), Aqua (5), Aura (5) – TOTAL 15**
Chinese ASAT Destruction of Fengyun-1C
(January 11, 2007)

FENGYUN 1C DEBRIS March 2007

Images courtesy NASA Orbital Debris Program Office
EOS Terra vs 31410 (Fengyun-1C Debris) Debris Avoidance Maneuver

• 2nd EOS Terra Debris Avoidance Maneuver (DAM)
  – June 22, 2007
  – Peak Pc of about 1:6
  – Minimum miss distance about 19 meters
  – Mitigated by 1.35 second mini-drag make-up maneuver
  – Burn at TCA minus 24-hours
  – Miss distance → about 1.2 km
  – Pc → 0

• 1st NASA Robotic Mission DAM vs. Fengyun-1C Debris

CREDIT: NASA Robotic Mission CARA Team
NASA Moves Terra Satellite to Avoid Debris Caused by Chinese A-Sat Test

BRIAN BERGER, WASHINGTON

Flight controllers at NASA’s Goddard Space Flight Center, Greenbelt, Md., had to maneuver the Terra environmental spacecraft in late June to avoid orbital debris created by the Jan. 11 test of a Chinese anti-satellite (A-Sat) weapon.

NASA officials said July 6 that the event marked the first time the agency has had to move one of its spacecraft to avoid a potential collision with debris created by the controversial Chinese A-Sat test.

A defunct Chinese weather satellite, Fengyun 1-C, was orbiting at an altitude of roughly 850 kilometers when it was destroyed Jan. 11 after being struck by a kinetic energy A-Sat weapon, producing a cloud of debris that is being tracked by the U.S. military’s Space Surveillance Network.

A “Terra Mission Status Update” posted on the U.S. space agency’s Web site says Goddard the satellite out of harm’s way. The resulting momentum raised the working satellite. “This was a pretty large piece
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) Debris Avoidance Maneuver

- 1st EOS Aura DAM
  - June 26, 2008
  - Peak Pc of about 1:2
  - Minimum miss distance about 11 meters (half the size of Aura)
  - Mitigated by 2.0 second mini-drag make-up maneuver
  - Burn at TCA minus 24-hours
  - Miss distance $\rightarrow$ about 500 meters
  - Pc $\rightarrow$ 0

EOS Aqua vs. 30420 (Fengyun 1C Debris) Debris Avoidance Maneuver

- **1st EOS Aqua DAM**
  - November 25, 2009
  - Peak Pc of about 1:14
  - Minimum miss distance of about 25 meters
  - Mitigated by 1.25 sec mini-drag make-up maneuver
  - Burn at TCA minus 24-hours
  - Miss Distance $\rightarrow$ about 560 meters
  - Pc $\rightarrow$ 0

Maneuver options limited due to routine drag make up maneuver performed 8-days prior to TCA
EOS Aura and Shijian (SJ)-11-02 satellite conjunction with active satellite

- On September 3, 2013, there was a predicted close approach between the EOS Aura satellite and the Shijian (SJ)-11-02 satellite.

- Second in a series of SJ-11 satellites launched by China into an orbit very similar to that of the Morning and Afternoon Constellations.

- Aura flight controllers prepared a RMM to avoid the close approach. They did not know whether SJ-11-02 was capable of maneuvering.

- A request was sent through the US State Department to its Chinese counterpart to let their space agency know of NASA's planned maneuver.

- Both satellites maneuvered within hours of each other.

- Fortunately, the 2 maneuvers mitigated the risk.

- Example of the need to improve communication with non-constellation satellites.
## EOS Debris Avoidance and Risk Mitigation Maneuvers (DAMs & RMMs) 2005-2014

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<tr>
<th>Primary</th>
<th>Secondary Number</th>
<th>Secondary Description</th>
<th>Maneuver Date</th>
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<th>Minimum Miss Distance (m)</th>
<th>Maximum Pc</th>
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CREDIT: NASA Robotic Mission CARA Team
# EOS Maneuvers Postponed or Re-planned (2005 – 2014)

As much or more effort as RMMs/DAMs

CREDIT: NASA Robotic Mission CARA Team
EOS Debris Avoidance Activities (January 2011 – April 2015)

T1 – Notify (email/phone), T2 – Conduct Briefing
T3 – Plan Maneuver, T4 – Execute Maneuver

CREDIT: CARA Team & Eric Moyer
EOS High Interest Events (HIEs) (2010 – 2014)

2010: 17 HIEs – 2 DARMs – 4 required significant effort
2011: 85 HIEs – 9 DARMs – 16 required significant effort
2012: 72 HIEs – 4 DARMs – 9 HIEs required significant effort
2013: 81 HIEs – 13 DARMs – 31 HIEs required significant effort
   • 3 “Surprise” HIEs requiring emergency/short-notice DAMs (Terra 1, Aqua 2)
   • First HIE with operational Chinese satellite (Aura maneuvered on 9/2/2013)
   • 5 Routine maneuvers postponed and/or rescheduled (0 Terra, 2 Aqua and 3 Aura)
   • 24 DAMs planned, 10 executed, 14 self-mitigated or approved and waived-off
2014: 91 HIEs – 10 DARMs – 36 HIEs required significant effort
   • 1 “Surprise” HIEs requiring emergency/short-notice DAMs (Aqua on 10/21)
   • 6 Routine maneuvers postponed and/or rescheduled (3 Terra, 2 Aqua and 1 Aura)
   • 35 DAMs planned, 6 executed, 29 self-mitigated or approved and waived-off (2)

Debris Avoidance Related Maneuver (DARM)
   • Maneuver planned and executed
   • Planned maneuver postponed
EOS Aqua Conjunction Assessment Statistics
(January 2005 to March 2015)

CREDIT: CARA Team & Ryan Frigm
A-Train Systematic Conjunctions
A-Train
Afternoon Constellation
Systematic Conjunctions
Situation is similar near the South Pole crossings.
Landsat-5 Conjunctions with the A-Train (Afternoon Constellation)

- The Morning Constellation and Afternoon Constellation satellites follow similar 705 km polar sun-synchronous orbits.
- Orbit planes intersect near the poles.
- In February 2010, monitoring results indicated that Landsat-5 was crossing through the orbit plane intersections at the poles between CloudSat and CALIPSO.
- Further investigation revealed that Landsat-5 had “passed” through the Afternoon Constellation in 2004 and 2008.
- NASA formed a “Red Team” in March 2010 to analyze the situation and determine the best courses of action to minimize risks while continuing to meet mission requirements.
Landsat-5/A-Train Orbit Crossing Coordination Plan (Red Team)

Earth Science Mission Operations Project
428-10-TBS

Afternoon Constellation / Landsat 5 Orbit Crossing Coordination Plan

July 2010
Expires: July 2015

This document contains sensitive information and shall be handled in a way that precludes its disclosure to the general public and limits its circulation for EOS Program use only.

Independent Review of the CA Process for NASA Robotic Assets (Tiger Team)

Tiger Team Independent Review of the Conjunction Assessment Process for NASA Robotic Assets

Final Report

Version 11

December 22, 2010
STRATEGY FOR MITIGATING COLLISIONS BETWEEN LANDSAT-5 AND THE AFTERNOON CONSTELLATION

Joshua A. Levi† and Eric J. Palmer†

The NASA Goddard Space Flight Center Earth Science Mission Operations project, the French space agency Centre National d’Études Spatiales, the Argentinian space agency Comisión Nacional de Actividades Espaciales, and the United States Geological Survey all operate spacecraft in sun-synchronous frozen orbits. The orbits are planned to not place any of the spacecraft at risk of colliding with another. However, evolution of these orbits over time has compromised the safe interaction between Landsat-5 and the Afternoon Constellation. This paper analyzes the interactions between the Landsat-5 spacecraft and the Afternoon Constellation members over a period of 6 years, describing the current risk and plan to mitigate collisions in the future.
CloudSat under-flight of Aqua in 2011

- 4/17 CloudSat battery anomaly
  - CloudSat unable to maneuver and drifting towards Aqua
  - predicted to pass under Aqua around June 9-13th
- Weekly coordination meetings
- Postponed 5/19 Aqua DMUM
  - Aqua would drift towards CloudSat
- Considered multiple maneuver options to maximize radial separation at the time of the passing
- 6/5 Aqua +10km CB violation
- 6/8 Aqua DMUM (part 1)
- 6/18 CloudSat orbit lowering
- 6/18 CloudSat passes under Aqua
- 6/22 Aqua DMUM (part 2)

CREDIT: EOS Flight Dynamics Team
SAC-C crossing the Afternoon Constellation (A-Train)

- May 2011: SAC-C anomaly left spacecraft unable to maneuver
  - Declared lost August 2013
  - Safely crossed all Earth Science Constellation member satellites in 2013/2014

<table>
<thead>
<tr>
<th>Spacecraft</th>
<th>Estimated Crossing Date</th>
<th>Radial Separation (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LandSat-8</td>
<td>Nov. 25, 2013</td>
<td>-4 to -2</td>
</tr>
<tr>
<td>Aura</td>
<td>Dec. 11, 2013</td>
<td>-1.3 to -0.3</td>
</tr>
<tr>
<td>LandSat-7</td>
<td>Dec. 20, 2013</td>
<td>-1.5</td>
</tr>
<tr>
<td>CloudSat</td>
<td>Jan. 5, 2014</td>
<td>-0.8 to 0</td>
</tr>
<tr>
<td>CALIPSO</td>
<td>Jan. 9, 2014</td>
<td>-1 to 0</td>
</tr>
<tr>
<td>Aqua</td>
<td>Jan. 14, 2014</td>
<td>-1 to 0</td>
</tr>
<tr>
<td>GCOM-W1</td>
<td>Jan 31, 2014</td>
<td>-0.7 to 0.8</td>
</tr>
<tr>
<td>Terra</td>
<td>Mar. 30, 2014</td>
<td>0.5 to 1.5</td>
</tr>
</tbody>
</table>
Future Challenges
Debris Population Projected to get Worse

Note: Five-fold increase from 2005 to 2010

Note: Predicted to get slightly worse thru 2020

CREDIT: NASA/JSC Orbital Debris Program Office
Updated Space Fence
(200 – 250K Object Space Catalog)

Initial Operational Capability scheduled for 2017

CREDIT: Lockheed Martin
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.
   
   You knew Pluto wasn't a planet the first time you saw a drawing of the Solar System...in kindergarten.

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

3. You named your dog Hubble.

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

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

6. 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.

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

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

9. You know Space Fence isn’t really a fence.
EOS Challenges Encountered

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

• Spacecraft Constraints limit options (i.e. no retrograde maneuvers)

• Mission Orbit Maintenance and Constellation Flying Requirements that limit response

• Operational Constraints that determine minimum turn-around time

• Limited Resources
EOS Observations and/or Lessons Learned

• 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 *

Collision Avoidance

Coordination of Predicted Conjunctions Between NASA Satellites and Satellites of Other Countries

International Earth Observing Constellations
Satellites from the U.S., Japan, and France fly within seconds to minutes of each other to enable near simultaneous observations of the Earth systems (land, oceans, and atmosphere). They operate in polar, sun-synchronous 16-day repeating orbits at an altitude of 706 km. Sensors/instruments are provided by U.S., Japan, United Kingdom, Canada, France, The Netherlands and Brazil.
- Morning Conjunction: cross the equator between 10:30 a.m. - 10:45 a.m. Mean Local Time (MLT)
- Afternoon Conjunction (known as the A Train): cross the equator between 1:30 p.m. - 1:45 p.m. MLT.

Satellite Safety Website
- Satellite Safety
  - Promotes safety
  - Facilitates communications between satellite operators
  - Provides information to other satellite operators about NASA and constellation missions:
    a. Constellation mission descriptions (including maneuvering requirements)
    b. Constellation contact persons at the NASA control centers
  - Plan to provide additional information to an operator involved in a high-risk predicted close approach with a NASA satellite

NASA’s Approach to Satellite Safety
- Constellation operators maintain their location to satisfy science requirements
- Monitoring is performed to ensure safety
  1. Conjunction Assessment Risk Analysis (CARA) Team
     - Monitors all NASA satellites and related constellation satellites
     - Notifies the affected mission team if a potential threat from a space object is detected
  2. Constellation Coordination System (CCS)
     a. Web-based system
     b. Monitors constellation configuration and provides warnings of predicted deviations
     c. Used to share mission products and spacecraft status
     d. Includes tools for further flight dynamics analysis and visualizations
- If needed, the satellite operators perform risk mitigation maneuvers

Space Objects
- Maneuverable Satellites
  - Satellites that change their orbit periodically, usually to maintain their required orbital location
  - As needed, satellites maneuver to avoid a close approach with other space objects
- Non-Maneuverable Satellites
  - Some active satellites lacking propulsion systems
  - Satellites out of fuel
- Non-manuverable Objects
  - Orbital debris (estimated: 900,000 between 1 and 10 cm, 100 million less than 1 cm)

Case History: A-Train and Landsat 5
- In 2010, Landsat 5 crossed through the A-Train orbital plane elevating the risk of close approaches with A-Train satellites.
- NASA and USGS adopted a “managed crossing approach” that took advantage of the highly predictable nature of the orbits. Procedures were documented and implemented.
- Coordination and timely communications are key to keeping all satellites at the 706 km orbit safe.

http://satellitesafety.gsfc.nasa.gov/
Collision avoidance: Coordination of predicted conjunctions between NASA satellites and satellites of other countries

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ABSTRACT

This paper describes one of the challenges facing the flight operations teams of the International Earth Observing constellation satellites at the 705 km orbit, including National Aeronautics and Space Administration (NASA) satellites. The NASA Earth Science Mission Operations (ESMO) Project has been dealing with predicted conjunctions (close approaches) between operational/non-operational space objects and the satellites in the International Earth observing constellations for several years.

The NASA Conjunction Analysis and Risk Assessment (CARA) team provides daily reports to the ESMO Project regarding any “close approach” high interest events (HIEs) involving the constellation satellites. The daily CARA reports provide risk assessments that help the operations teams to determine if they need to perform a risk mitigation action. If the conjuncting space object is an operational satellite that is capable of maneuvering, the affected satellite team needs to coordinate their action plan with the operator of the conjuncting satellite. It is absolutely critical for the two teams to communicate as soon as possible. The goal is to minimize the collision risk; for this to happen, both satellite operators need to coordinate their maneuver plans.

The constellation teams have established guidelines for coordinating HIEs among themselves. This coordination process has worked successfully for several years for satellites that are operated by other organizations in the United States and by NASA’s international partners, all with whom NASA has a cooperative agreement. However, the situation is different for predicted conjunctions with satellites of foreign operators that do not have an agreement with NASA and the constellation organizations. The current process for coordinating conjunctions is neither timely nor satisfactory. Due to the concern that the Earth observing satellites at the 705 km orbit can become unusable by a collision with other satellites, the NASA ESMO Project and the CARA team are proposing a more timely coordination and communication process to resolve and safely mitigate these predicted high-risk events. This proposed process does not violate any existing communication constraints between the United States and certain foreign operators. Comments from other satellite operators are welcomed and greatly appreciated.
Do you believe?

“For those who believe, no explanation is necessary; for those who do not believe, no explanation is possible.”

- 1943 film “The Song of Bernadette”

Thank you for your time

Merci bien
Questions