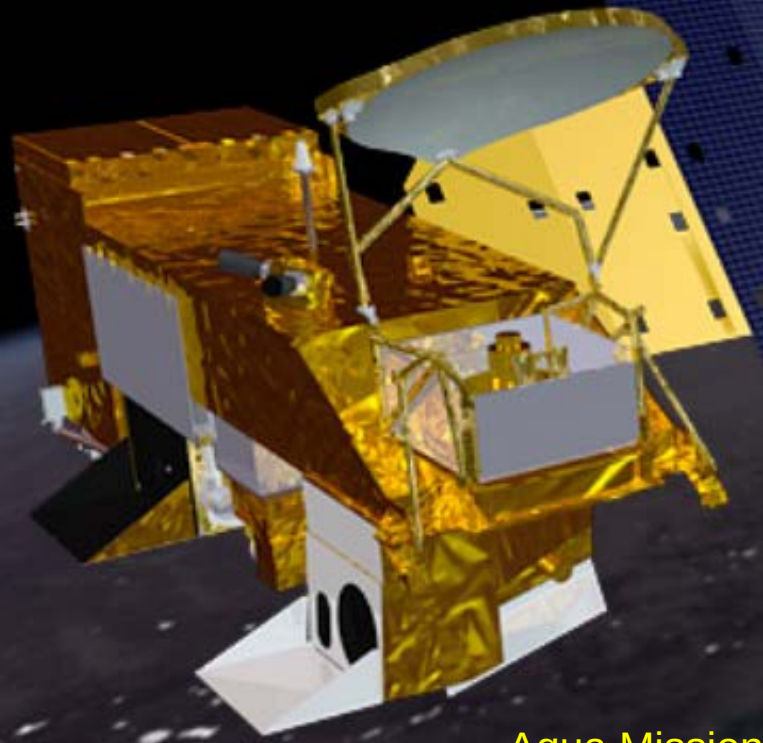
2018 Space Situational Awareness OPERATORS' WORKSHOP



November 13-16, 2018

To Maneuver or Not to Maneuver That is the Question

Bill Guit

Aqua Mission Director – Code 584/428
Mission Validation and Operations Branch
Earth Science Mission Operations (ESMO) Project
Goddard Space Flight Center (GSFC)
National Aeronautics and Space Administration (NASA)

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301-614-5188

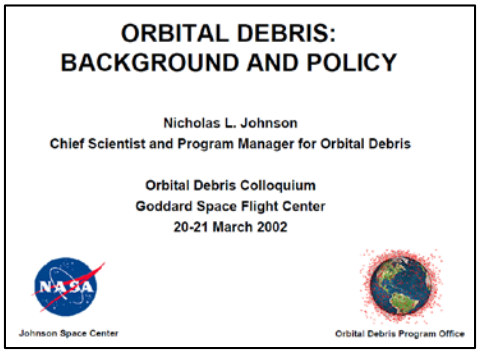
Topics

- 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

Early Days – The Beginning

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)
  - EP/EUVE Reentry (January 31, 2002)
- **Landsat-7 Conjunction Assessment Study (January 2002)**
  - Multiple conjunctions per day
  - Began working to establish procedures for ongoing support to ESMO EOS missions


ORBITAL DEBRIS:
BACKGROUND AND POLICY

Nicholas L. Johnson
Chief Scientist and Program Manager for Orbital Debris

Orbital Debris Colloquium
Goddard Space Flight Center
20-21 March 2002

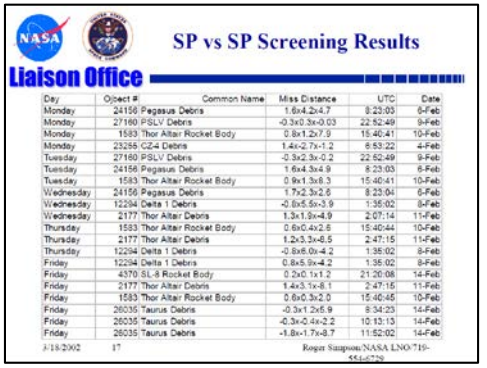
Johnson Space Center

Orbital Debris Program Office


Liaison Office

Space Situational Awareness
Launch - Orbit - Decommission

Roger D. Simpson
NASA Liaison to USSPACECOM
Peterson AFB, Colorado Springs, Co
719-554-6729


SP vs SP Screening Results

Liaison Office

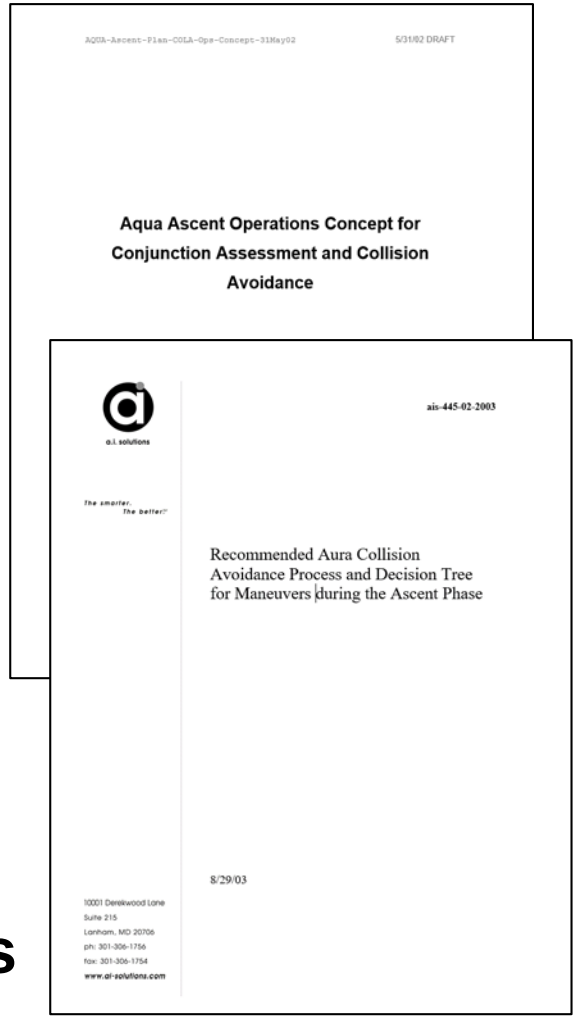
Day	Object #	Common Name	Miss Distance	UTC	Date
Monday	24156	Pegasus Debris	1.6x4.2x-4.7	8:23:03	6-Feb
Monday	27160	PSLV Debris	-0.3x0.3x-0.03	22:52:49	9-Feb
Monday	1583	Thor Altair Rocket Body	0.8x1.2x7.9	15:40:41	10-Feb
Monday	23255	CZ-4 Debris	1.4x-2.7x-1.2	6:53:22	4-Feb
Tuesday	27160	PSLV Debris	-0.3x2.3x-0.2	22:52:49	9-Feb
Tuesday	24156	Pegasus Debris	1.6x4.3x4.9	8:23:03	6-Feb
Tuesday	1583	Thor Altair Rocket Body	0.9x1.3x6.3	15:40:41	10-Feb
Wednesday	24156	Pegasus Debris	1.7x2.3x2.6	8:23:04	6-Feb
Wednesday	12294	Delta 1 Debris	-0.6x5.5x-3.9	1:36:02	8-Feb
Wednesday	2177	Thor Altair Debris	1.3x1.9x-4.9	2:07:14	11-Feb
Thursday	1583	Thor Altair Rocket Body	0.6x0.4x2.6	15:40:44	10-Feb
Thursday	2177	Thor Altair Debris	1.2x3.3x-8.5	2:47:15	11-Feb
Thursday	12294	Delta 1 Debris	-0.6x6.0x-4.2	1:36:02	8-Feb
Friday	12294	Delta 1 Debris	0.6x5.9x-4.2	1:36:02	8-Feb
Friday	4370	SL-8 Rocket Body	0.2x0.1x1.2	21:20:08	14-Feb
Friday	2177	Thor Altair Debris	1.4x3.1x-8.1	2:47:15	11-Feb
Friday	1583	Thor Altair Rocket Body	0.6x0.3x2.0	15:40:45	10-Feb
Friday	26035	Taurus Debris	-0.3x1.2x5.9	8:34:23	14-Feb
Friday	26035	Taurus Debris	-0.3x-0.4x-2.2	10:10:13	14-Feb
Friday	26035	Taurus Debris	-1.8x-1.7x-8.7	11:52:02	14-Feb

3/19/2002 17 Roger Simpson/NASA LNO/719-554-6729

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


AQUA-Ascent-Plan-COLA-Ops-Concept-31May02 5/31/02 DRAFT

Aqua Ascent Operations Concept for Conjunction Assessment and Collision Avoidance

ais-445-02-2003

o.i. solutions

"The smarter, The better!"

Recommended Aura Collision Avoidance Process and Decision Tree for Maneuvers during the Ascent Phase

8/29/03

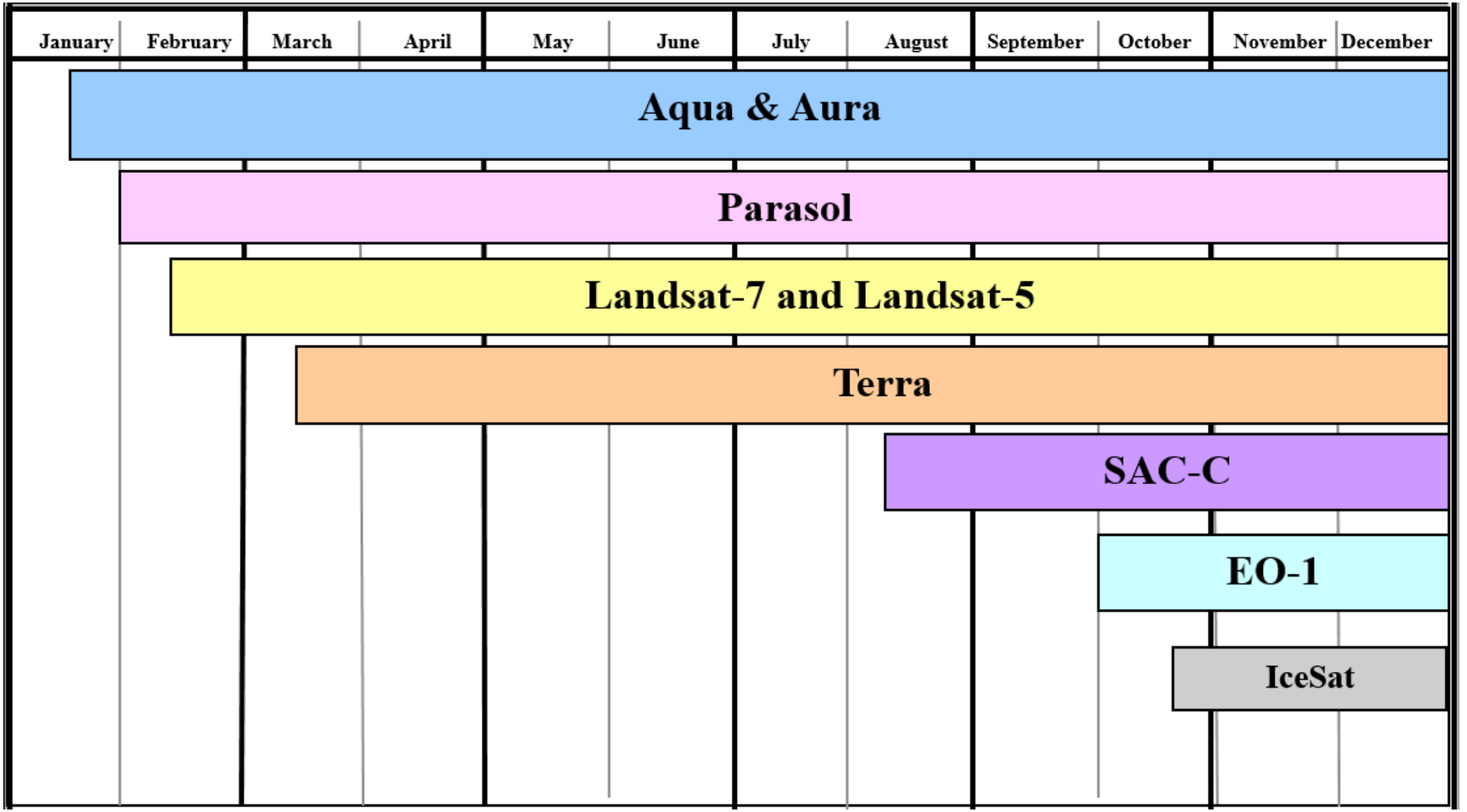
10001 Derekwood Lane
Suite 215
Lanham, MD 20706
ph: 301-306-1756
fax: 301-306-1754
www.oi-solutions.com

NASA Request to US Department of Defense (May 25, 2004)

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

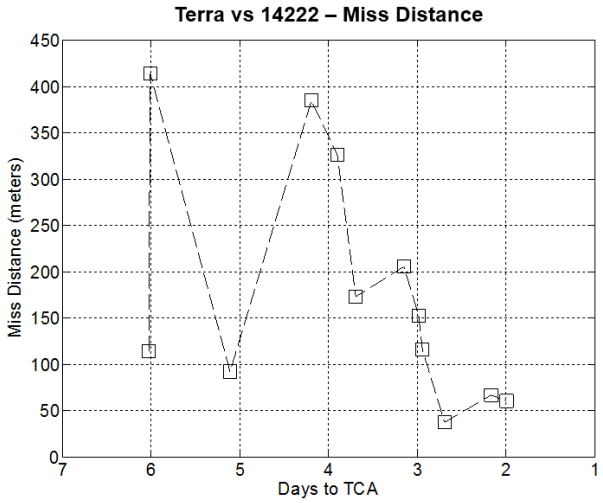
Routine Conjunction Assessment 2005 Screening Build-up

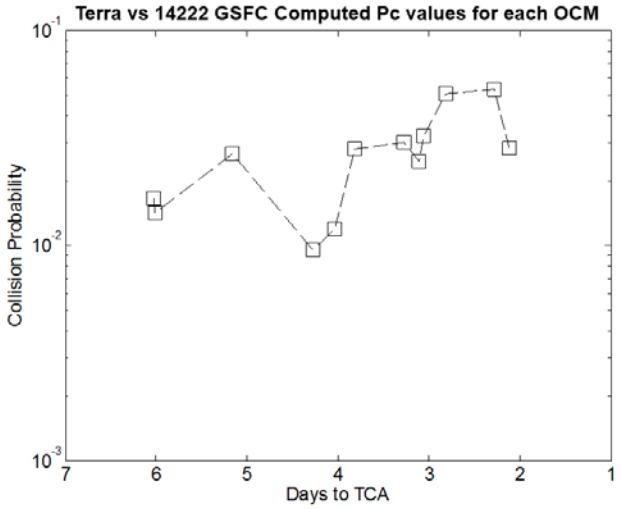


Early EOS Debris Avoidance Maneuvers

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)





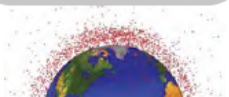
Reference: Lauri Newman and Matt Duncan, AIAA 2006-6291

1st NASA Robotic Mission DAM Makes the Front Page of

Orbital Debris Quarterly News

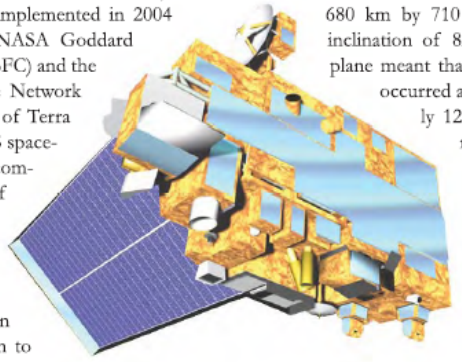
Volume 10, Issue 1
January 2006

Inside...



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.



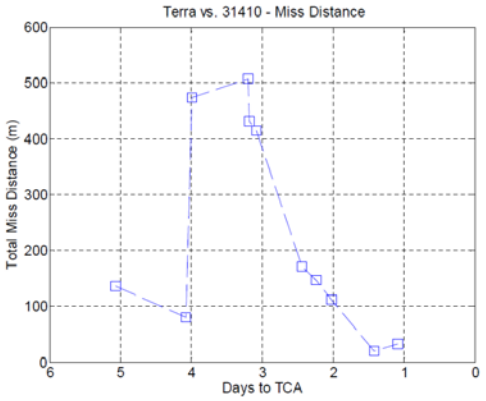
Terra (International Designator 1999-068A, U.S. Satellite Number 25994) was launched on 18 December 1999 on a nominal 6-year mission to monitor the complex nature of the Earth's atmosphere and surface. The nearly five-metric-ton spacecraft circles the Earth at an altitude of 705 km with an orbital inclination 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.

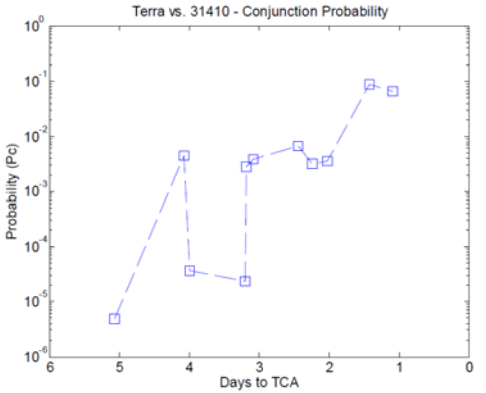
The Scout debris was in an orbit with an altitude similar to that of Terra (approximately 680 km by 710 km), but its posigrade inclination of 82.4° and different orbit plane meant that a collision would have occurred at a high velocity of nearly 12 km/s. By 21 October refined analysis of the future close 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)**

Made the Front Page of

SPACE NEWS
INTERNATIONAL
July 9, 2007
VOLUME 18 ISSUE 27 $4.95 ($7.50 Non-U.S.)

PROFILE/22>

BRIG. GEN. SUSAN MASHIKO

PROGRAM EXECUTIVE OFFICER, NATIONAL POLAR-ORBITING OPERATIONAL ENVIRONMENTAL SATELLITE SYSTEM

INSIDE THIS ISSUE

NASA Moves Terra Satellite to Avoid Debris Caused by Chinese A-Sat Test

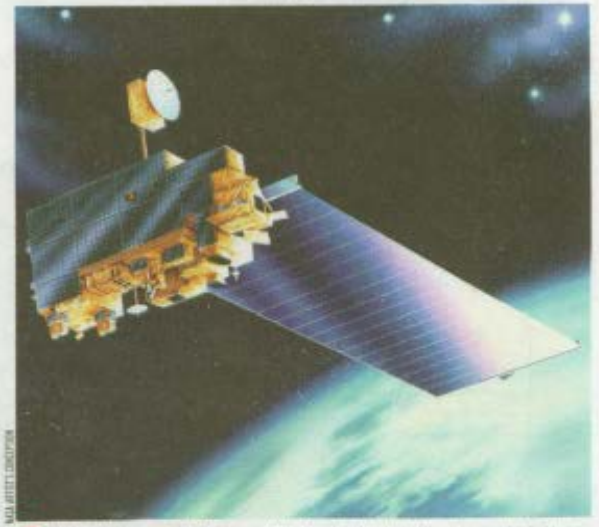
BRIAN BERGER, WASHINGTON

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



NASA ARTIST'S CONCEPTION

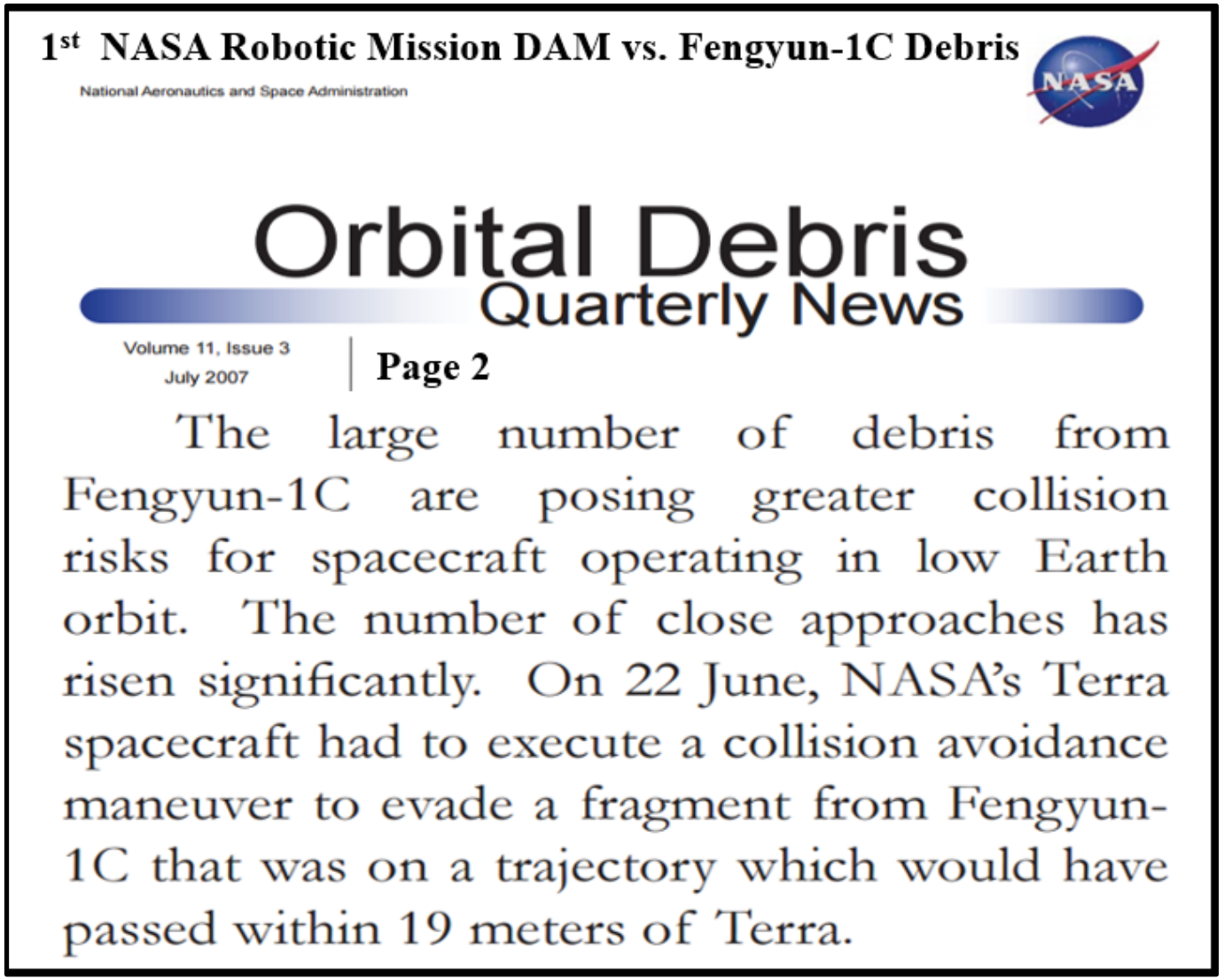
NASA said that repositioning the Terra satellite (above) marked the first time the agency has had to move one of its spacecraft to avoid a potential collision with debris created by the controversial Chinese A-Sat test.

the satellite out of harm's way. The resulting momentum raised

working satellite.

"This was a pretty large piece

But only page 2 in NASA/JSC's Orbital Debris Quarterly News



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

National Aeronautics and Space Administration

Orbital Debris Quarterly News

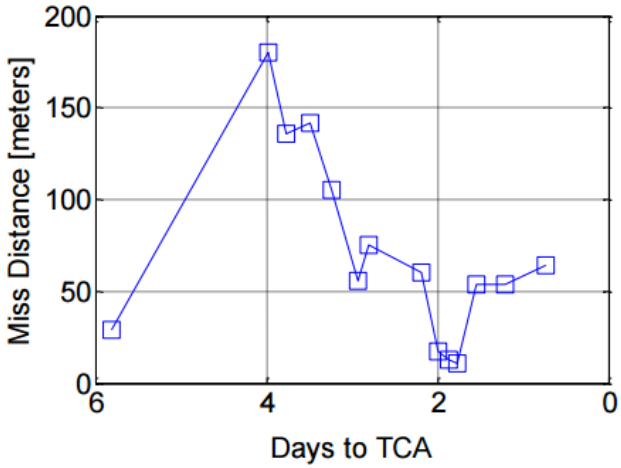
Volume 11, Issue 3
July 2007

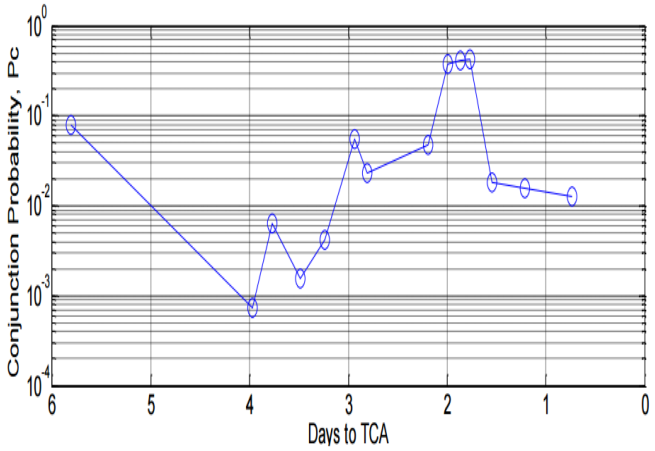
Page 2

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





Reference: Ryan C. Frigm, Joshua A. Levi, Dimitrios C. Mantziaras , AIAA 2010-1926

Jump forward 10-Years

Recent EOS Aqua Challenging Case Studies

Background

- **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

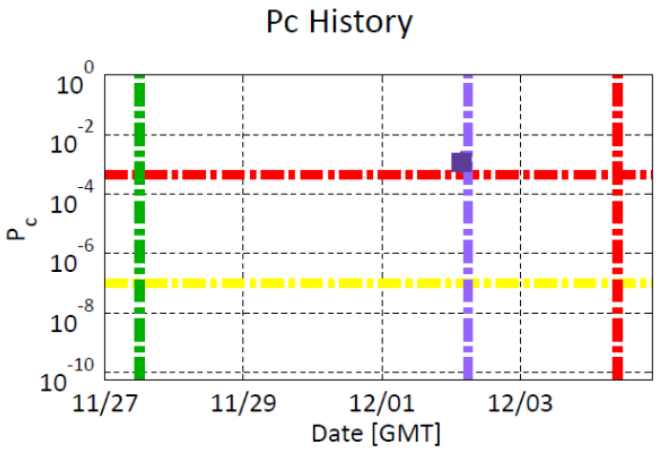
Aqua vs. 35917

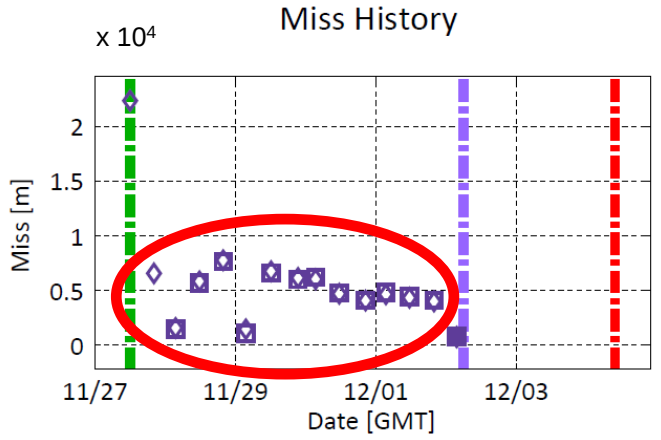
IRIDIUM-33 DEBRIS

TCA: 2017-12-05 at 05:27:59 GMT

EOS Aqua vs. 35917
(IRIDIUM 33 DEB)

- **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?**

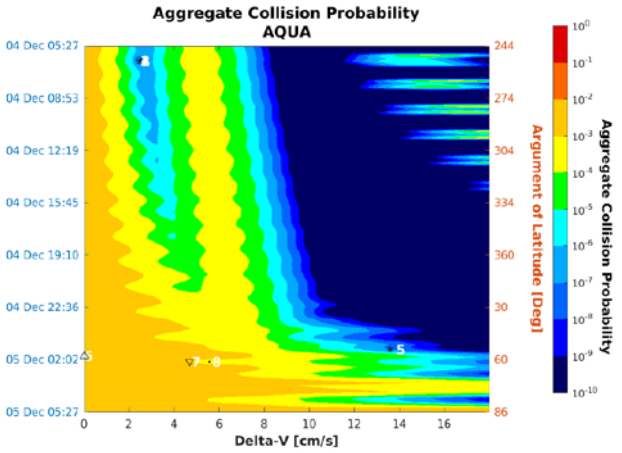


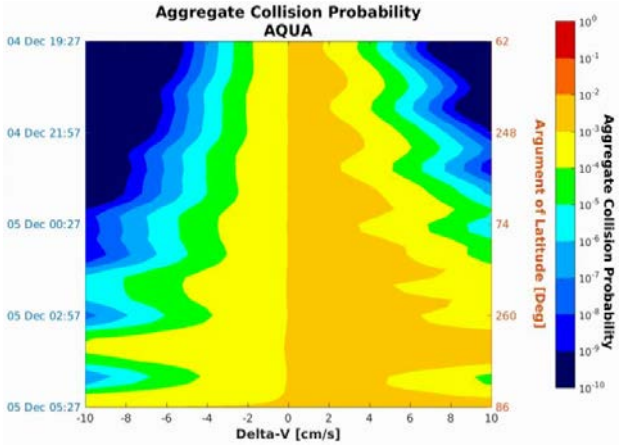


Credit: NASA Conjunction Assessment and Risk Analysis (CARA) Team

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

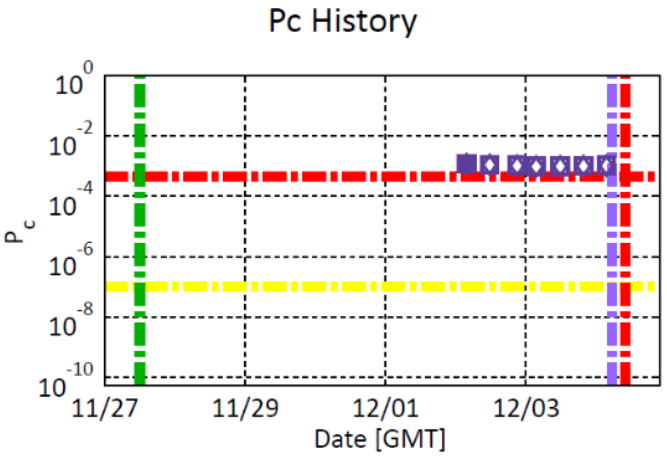


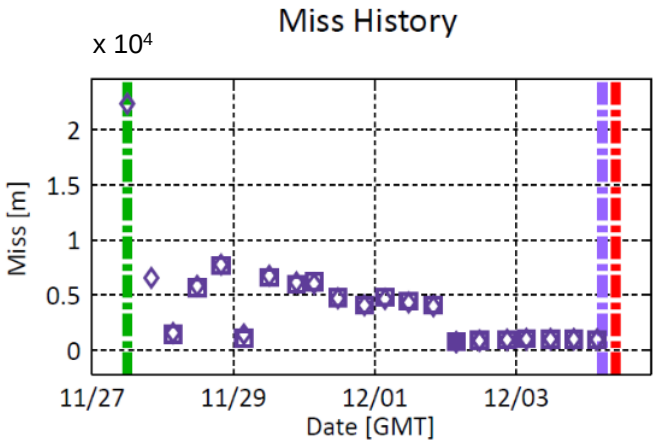


Credit: SpaceNav Collision Risk Management System (CRMS)

EOS Aqua vs. 35917
(Case Study #1)

- **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?**





EOS Aqua vs. 35917
(Case Study #1)

- **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

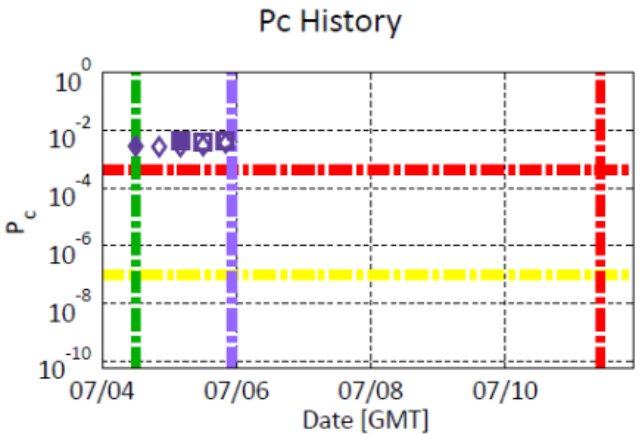
EOS Aqua vs. 37593
FENGYUN-1C DEB
SUMMARY

- **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

(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

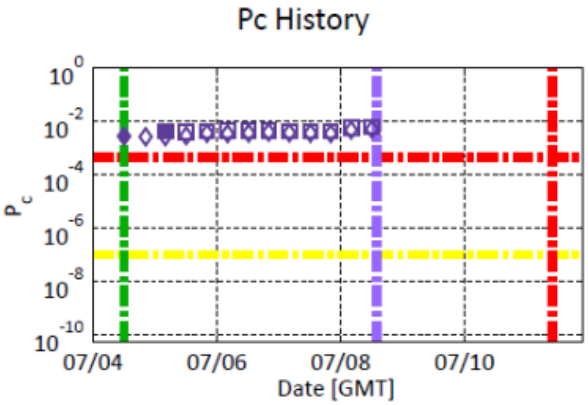


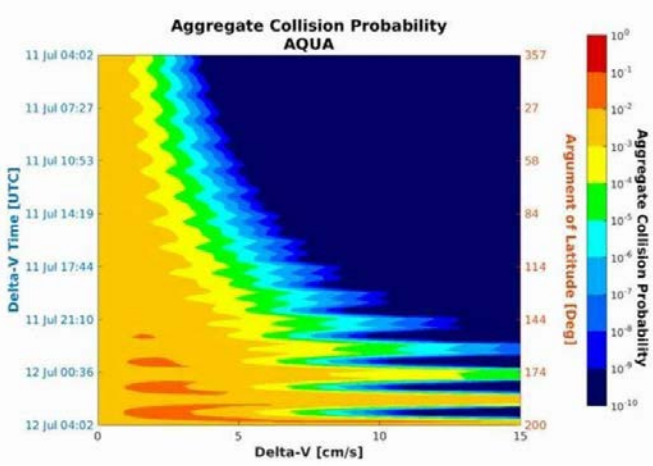
- **MD Assessment: Ample time to work the conjunction starting Monday morning – TCA is Wednesday evening local (Thursday 7/12 GMT day at 04:02:37 GMT)**
  - CRMS automatically starts generating maneuver options at TCA-3 days (AutoRMMs) **if secondary has been tracked in last 48-hours**

EOS Aqua vs. 37593

(Monday July 9th at 07:57 GMT: TCA minus 2.8-days)

- **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)

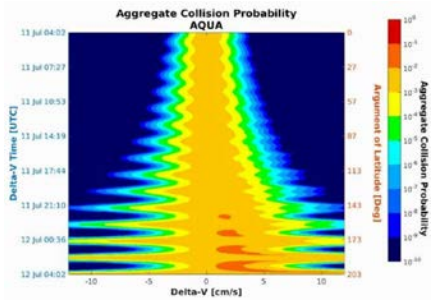
- **CARA Assessment: 9 July Afternoon Screening:**
  - Still no new tracking obtained; now 5 days since last track
  - Given average of about 1 track every two days, this is unexpected. However, the secondary was tasked at the highest level and single station tracked causing limited ability to further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

EOS Aqua vs. 37593

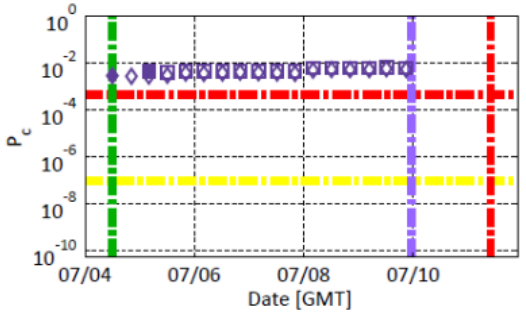
(Tuesday July 10th at 17:02 GMT: TCA minus 1.5-days)

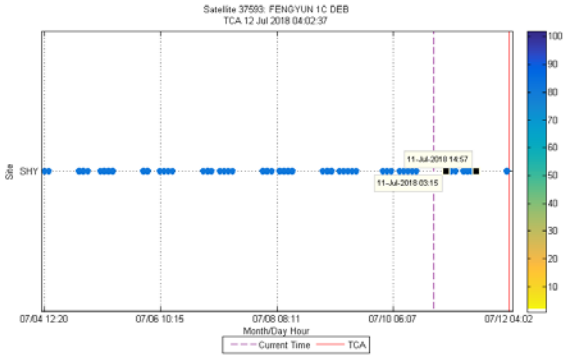
- **CRMS Manual Maneuver Planning**
  - CRMS not generating AutoRMMs (**stale data**)
  - Small RMM/DAM Delta-V Budgets
    - » Center, -10km, -20km about 2, 3, 4 cm/sec
  - Manually Generated/Screened **0** maneuvers
    - » **None were generated on Tuesday**
- **Significant internal (ESMO) discussion 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

CRMS MTS Plot
Retro-grade maneuver



Pc History

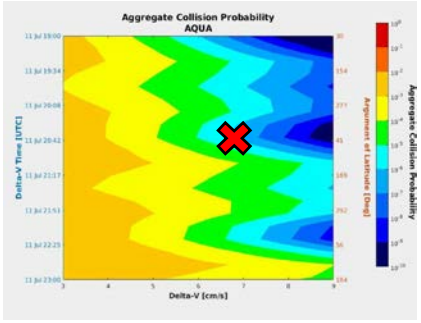


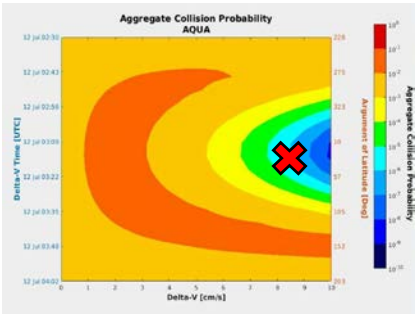


EOS Aqua vs. 37593

(Wednesday July 11th 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

EOS Aqua vs. 37593

(Wednesday July 11th 4:30pm ET CARA HIE Briefing)

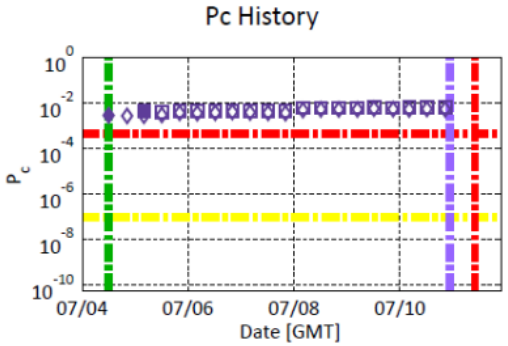
- **Secondary Orbit Determination (OD) Discussion**:
  - Secondary last tracked on 7/4 about 7-days ago
  - Object is not lost per discussion with CARA OSAs
  - OD Span contains 13 tracks over 17 days
  - OD Span is 17 days; EDR is 1E-4, At this EDR, OD Span is reasonable
  - Given OD Span, time since 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**

EOS Aqua vs. 37593

(Wednesday July 11th Evening at 7pm ET)

- **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-0.5d
  - ASW miss distance of 80.6 meters at TCA-0.5d
    - » 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?**

CARA Pc History Plot TCA-0.5



Total of 7 DAMs Screened
6.8 (7/11) and 8.5
&
3.0 and 4.0
&
5.5, 6.5 and 7.5

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)

Year	Terra 25994	Aqua 27424	Aura 28376	Total
2005	1	0	0	1
2006	0	0	0	0
2007	1	0	0	1
2008	0	0	1	1
2009	0	1	0	1
2010	1	0	1	2
2011	0	3	0	3
2012	0	0	1	1
2013	3	4	1	8
2014	3	1	1	5
2015	2	0	0	2
2016	0	0	2	2
2017	1	0	1	2
2018	2	1	0	3
TOTAL	14	10	8	32

EOS Debris Avoidance Maneuvers

(2005 – 2014)

Maneuver Number	Primary Object	Secondary Object Number	Secondary Object Description	Maneuver Date	Time of Closest Approach (GMT)	Minimum Miss Distance Observed [m]	Maximum Pc Observed
1	Terra	14222	SCOUT G-1	21 Oct 2005	23 Oct 2005 20:53	37	8.20E-02
2	Terra	31410	Fengyun 1-C Debris	22 Jun 2007	23 Jun 2007 21:44	18	1.60E-01
3	Aura	1399	TRIAD 1 Debris	26 Jun 2008	27 Jun 2008 15:34	11	4.80E-01
4	Aqua	30420	Fengyun 1-C Debris	25 Nov 2009	26 Nov 2009 15:36	25	7.00E-02
5	Terra	34700	Iridium 33 Debris	22 Jan 2010	23 Jan 2010 20:46	244	5.70E-03
6	Aura	30262	Cosmos 2251 Debris	22 Nov 2010	24 Nov 2010 11:16	50	3.90E-02
7	Aqua	35957	Cosmos 2251 Debris	02 Jan 2011	05 Jan 2011 18:17	94	8.40E-03
8	Aqua	34494	Iridium 33 Debris	08 Feb 2011	08 Feb 2011 19:32	41	4.70E-02
9	Aqua	4917	Thorad Agena D Debris	01 Mar 2011	02 Mar 2011 02:45	204	3.41E-03
10	Aura	34574	Cosmos 2251 Debris	16 May 2012	17 May 2012 19:09	81	4.70E-04
11	Aqua	407	Thor Ablestar Debris	10 Mar 2013	12 Mar 2013 04:02	860	2.57E-03
12	Aqua	35733	Iridum 33 Debris	23 Mar 2013	24 Mar 2013 00:30	84	2.40E-02
13	Terra	12343	Cosmos 1174 Debris	24 Mar 2013	26 Mar 2013 04:24	113	2.38E-03
14	Terra	26209	CZ-4 Debris	18 Aug 2013	19 Aug 2013 07:43	79	6.72E-02
15	Aura	37765	SJ-11-02	02 Sep 2013	03 Sep 2013 04:02	320	2.23E-04
16	Aqua	34510	Iridium 33 Debris	25 Oct 2013	25 Oct 2013 04:27	689	8.99E-04
17	Terra	31201	Fengyun 1C Debris	17 Nov 2013	18 Nov 2013 05:42	272	1.01E-02
18	Aqua	35652	Cosmos 2251 Debris	28 Nov 2013	28 Nov 2013 22:28	373	6.41E-04
19	Terra	26347	CZ-4 Debris	10 Feb 2014	10 Feb 2014 11:52	152	1.24E-02
20	Terra	9040	Delta 1 Debris	21 Mar 2014	23 Mar 2014 00:17	50	2.35E-03
21	Aura	36712	Fengyun 1C Debris	29 Aug 2014	02 Sep 2014 12:32	408	1.19E-03
22	Aqua	81180	Unknown	21 Oct 2014	21 Oct 2014 04:17	4935	6.90E-04
23	Terra	35925	Iridium 33 Debris	31 Dec 2014	01 Jan 2015 06:24	206	9.67E-04

EOS Debris Avoidance Maneuvers

(2015 – 2018-08-30)

Maneuver Number	Primary Object	Secondary Object Number	Secondary Object Description	Maneuver Date	TCA (GMT)	Minimum Miss Distance Observed [m]	Maximum Pc Observed
24	Terra	35600	Cosmos 2251 Debris	27 May 2015	27 May 2015 23:13	57	1.86E-02
25	Terra	87692	AnalystSat	16 Jun 2015	16 Jun 2015 08:33	70	5.26E-02
26	Aura	34215	CBERS 1 Deb	18 Jan 2016	19 Jan 2016 01:17	143	1.57E-03
26	Aura	34726	COSMOS 2251 Deb	15 Mar 2016	16 Mar 2016 08:27	19	3.36E-01
28	Aura	25759	PSLV R/B	26 Mar 2017	26 Mar 2017 13:39	95	3.45E-02
29	Terra	35627	IRIDIUM 33 Deb	05 Jul 2017	06 Jul 2017 04:26	176	1.55E-03
30	Terra	33666	FENGYUN 1C Deb	15 Mar 2018	16 Mar 2018 17:35	245	1.97E-03
31	Aqua	37593	FENGYUN 1C DEB	12 Jul 2018	12 Jul 2018 04:02	74.4	5.59E-03
32	Terra	81010	UNKNOWN	10 Aug 2018	11 Aug 2018 19:50	43.4	2.09E-02

DAMs Re-plans	Terra 25994	Aqua 27424	Aura 28376	Total
TOTAL DAMS	14	10	8	32
Postponed and or re-planned Maneuvers	6	15	16	37

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.

CREDIT: Lockheed Martin


Thank you for your time and attention
Questions

Abbreviations/Acronyms List

A-Sat – Anti-Satellite
ASW – Astrodynamics Workstation
CA – Conjunction Assessment
CAE – FOT Collision Avoidance Engineer
CAM – Command Authorization Meeting
CARA – Conjunction Assessment Risk Analysis
CGRO – Compton Gamma Ray Observatory
CMOC – Cheyenne Mountain Complex
CRMS – Collision Risk Management System
DAM – Debris Avoidance Maneuver
DMUM – Drag Make-up Maneuver
EDT – Eastern Daylight Time
EDR – Energy Dissipation Rate
EO-1 – Earth Observing-1 Satellite
EOS – Earth Observing System
ESC – Earth Science Constellation
ESMO – Earth Science Mission Operations
FDS – Flight Dynamics System
FOT – Flight Operations Team
FST – Flight Support Team
GMT – Greenwich Mean Time
GSFC – Goddard Space Flight Center
GTE – Ground Track Error
HIE – High Interest Event
HIEB – High Interest Event Briefing
HQ – Headquarters
km – kilometer
LUPI – Length of Update Interval
MD – Mission Director
MLT – Mean Local Time
MOWG – Mission Operations Working Group
MTS – Maneuver Trade Space
NASA – National Aeronautics & Space Administration
OD – Orbit Determination
OSA – Orbital Safety Analyst
Pc – Probability of Collision
RIC – Radial, In-track, Cross-Track
RMM – Risk Mitigation Maneuver
SAC-C – Scientific Application Satellite-C
SCOUT – Solid Controlled Orbital Unity Test
SP – Special Perturbations
TBD – To Be Determined
TCA – Time of Closest Approach
TDRSS – Tracking and Data Relay Satellite System
TRMM – Tropical Rainfall Measuring Mission
USSTRATCOM – United States Strategic Command
UT – Universal Time
UTC – Coordinated Universal Time