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

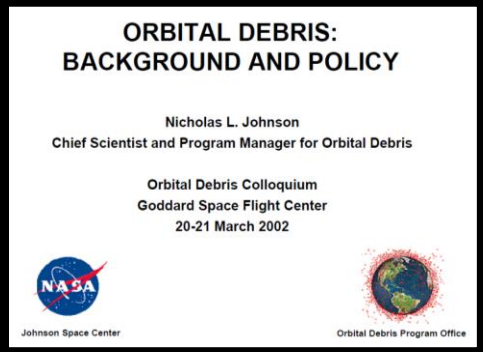
- Native American Proverb
- Haida Indian Saying

Images courtesy NASA Orbital Debris Program Office

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


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

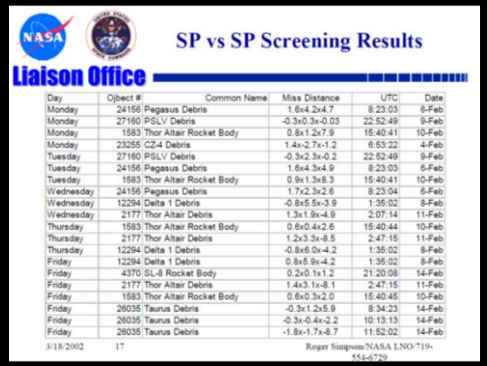
Johnson Space Center

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


Liaison Office

SP vs SP Screening Results

Day	Object #	Common Name	Miss Distance	UTC	Date
Monday	24156	Pegasus Debris	1.6x4.2x4.7	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	0.9x1.3x8.3	15:40:41	10-Feb
Wednesday	24156	Pegasus Debris	1.7x2.3x2.6	8:23:04	6-Feb
Wednesday	12294	Delta 1 Debris	-0.8x6.5x-3.9	1:35:02	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	-0.8x6.0x-4.2	1:35:02	8-Feb
Friday	12294	Delta 1 Debris	0.8x5.9x-4.2	1:35:02	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	10:13:13	14-Feb
Friday	26035	Taurus Debris	-1.8x-1.7x-8.7	11:52:02	14-Feb

3/18/2002 17 Roger Simpson/NASA LNO/719-554-6729

The Good, the Bad and the Ugly

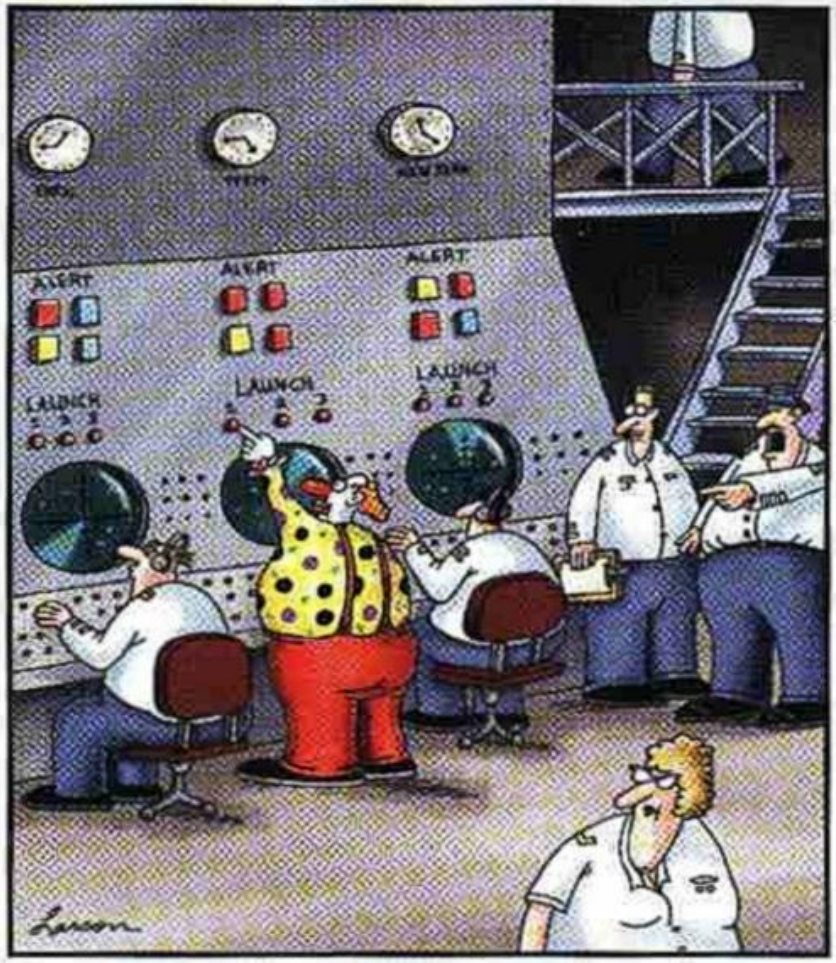
(Who to credit – or blame depending on your perspective)

- **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

Early Days – 2002
(EOS Aqua launch May 4, 2002)

Screened ascent maneuvers for EOS Aqua

Aqua Launch Control Room



"Hey! What's that clown think he's doing?"

The Far Side®
LAST IMPRESSIONS
2002

May

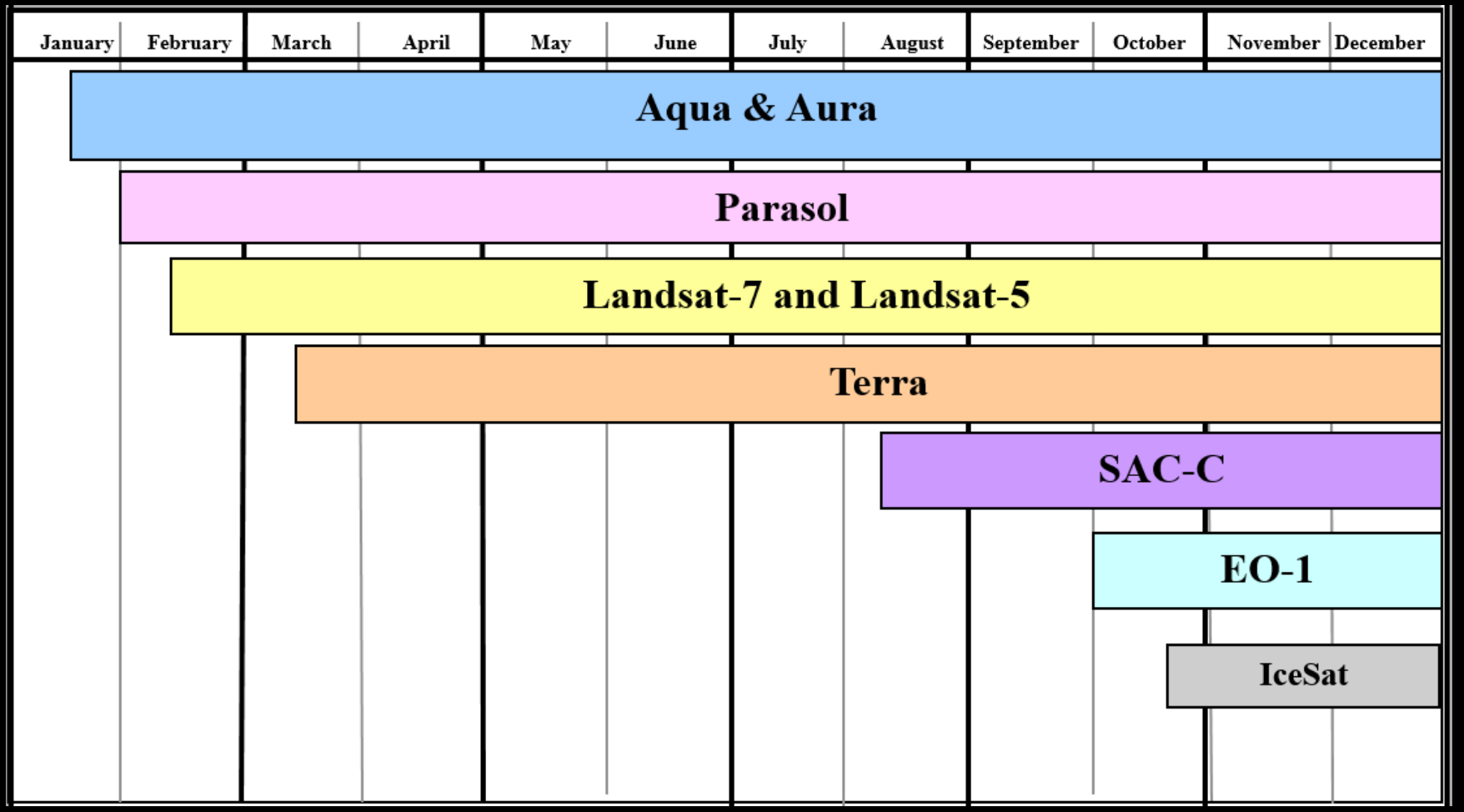
Saturday **4**

Early Days – 2004
(EOS Aura and PARASOL launches)

May 2004: NASA request to US Department of Defense to establish routine conjunction assessment process for NASA robotic missions

Screened ascent maneuvers for both missions

Routine Conjunction Assessment
2005 Screening Build-up



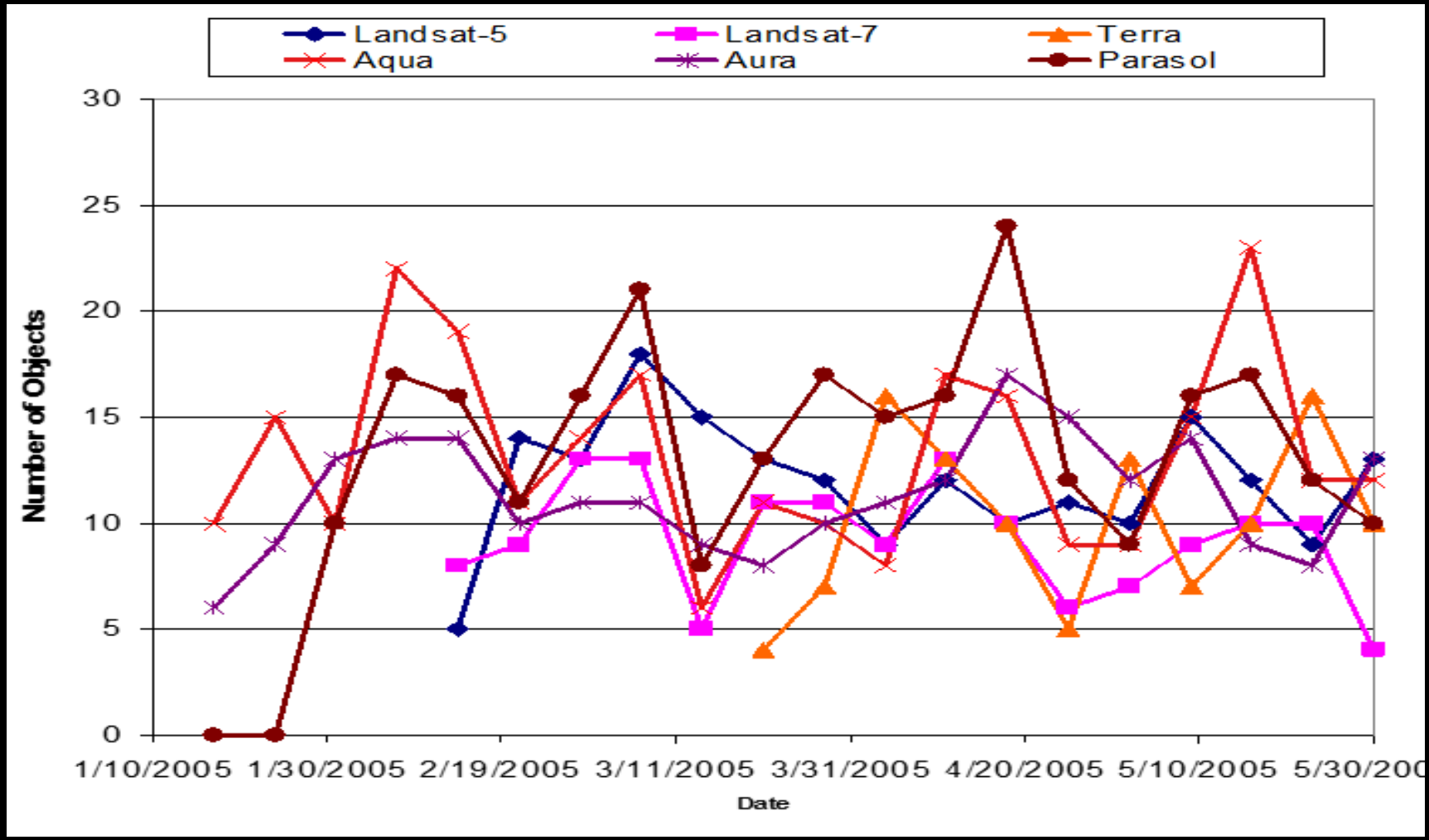
Early EOS Conjunction Assessment Experience (2005 – CARA began logging HIEs in May)

Primary	Secondary	TCA	Comments
Aura	82095	21-Jan-05	First EOS High Interest Event (HIE) Repeating Close Approach (CAs)
Aqua	11113	31-Jan-05	Predicted miss distance of 380 meters
Aqua	05808	05-Feb-05	Predicted miss distance of 69 meters
Aura	13465	20-Mar-05	Predicted miss distance of 31 meters
Terra	12194	24-Apr-05	Repeating CAs (8), Pc 1.6E-03 → 0
Aqua	03927	12-May-05	**Waived-off planned 5/11 routine drag make-up maneuver**
Terra	18665	17-May-05	Repeating CAs (6), additional CAs with 82095 and 87331
Terra	28370	25-May-05	Repeating CAs, near co-planar, low relative velocity CAs
Aqua	4579	06-Jun-05	
Aqua	89085	09-Jun-05	
Aqua	14345	19-Jun-05	
Aura	26181	26-Jul-05	
Aqua	87722	07-Aug-05	
Aura	27493	21-Aug-05	
Aqua	87278	18-Sep-05	
Terra	14222	23-Oct-05	**First NASA Robotic Mission Debris Avoidance Maneuver (DAM)**
Terra	26260	08-Nov-05	
Aura	19105	12-Nov-05	
Aura	24138	04-Dec-05	
Aqua	24097	06-Dec-05	**Waived-off planned routine drag make-up maneuver**

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

CREDIT: NASA Robotic Mission CARA Team

Early Conjunction Assessment Statistics (First half of 2005)



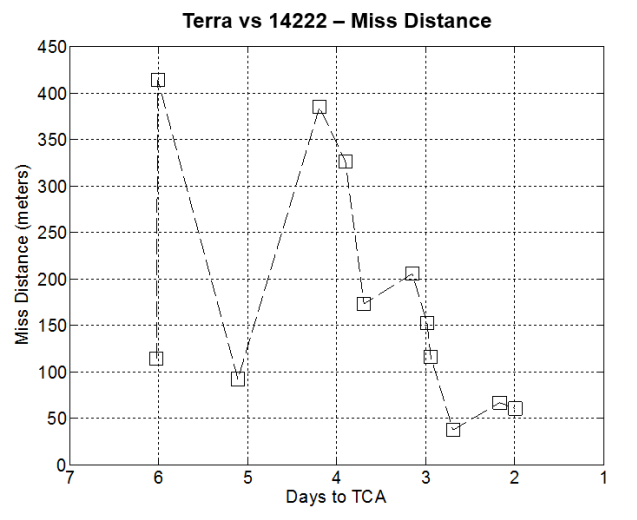
About 11 conjunctions per week per mission

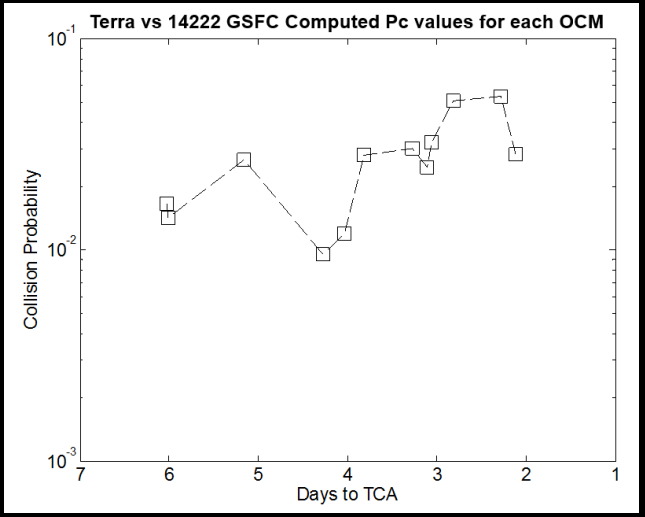
CREDIT: NASA Robotic Mission CARA Team

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

1st NASA Robotic Mission Debris Avoidance Maneuver (DAM)

National Aeronautics and Space Administration

Orbital Debris Quarterly News

Volume 10, Issue 1

January 2006

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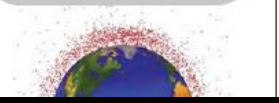
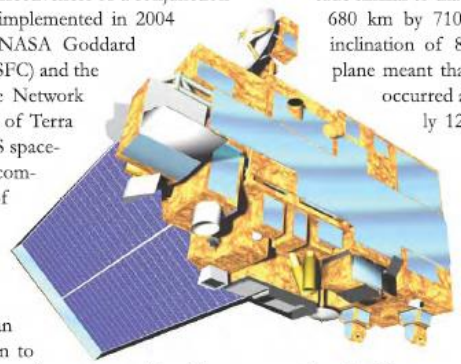


Collision Avoidance Maneuver Performed by NASA's Terra Spacecraft

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.

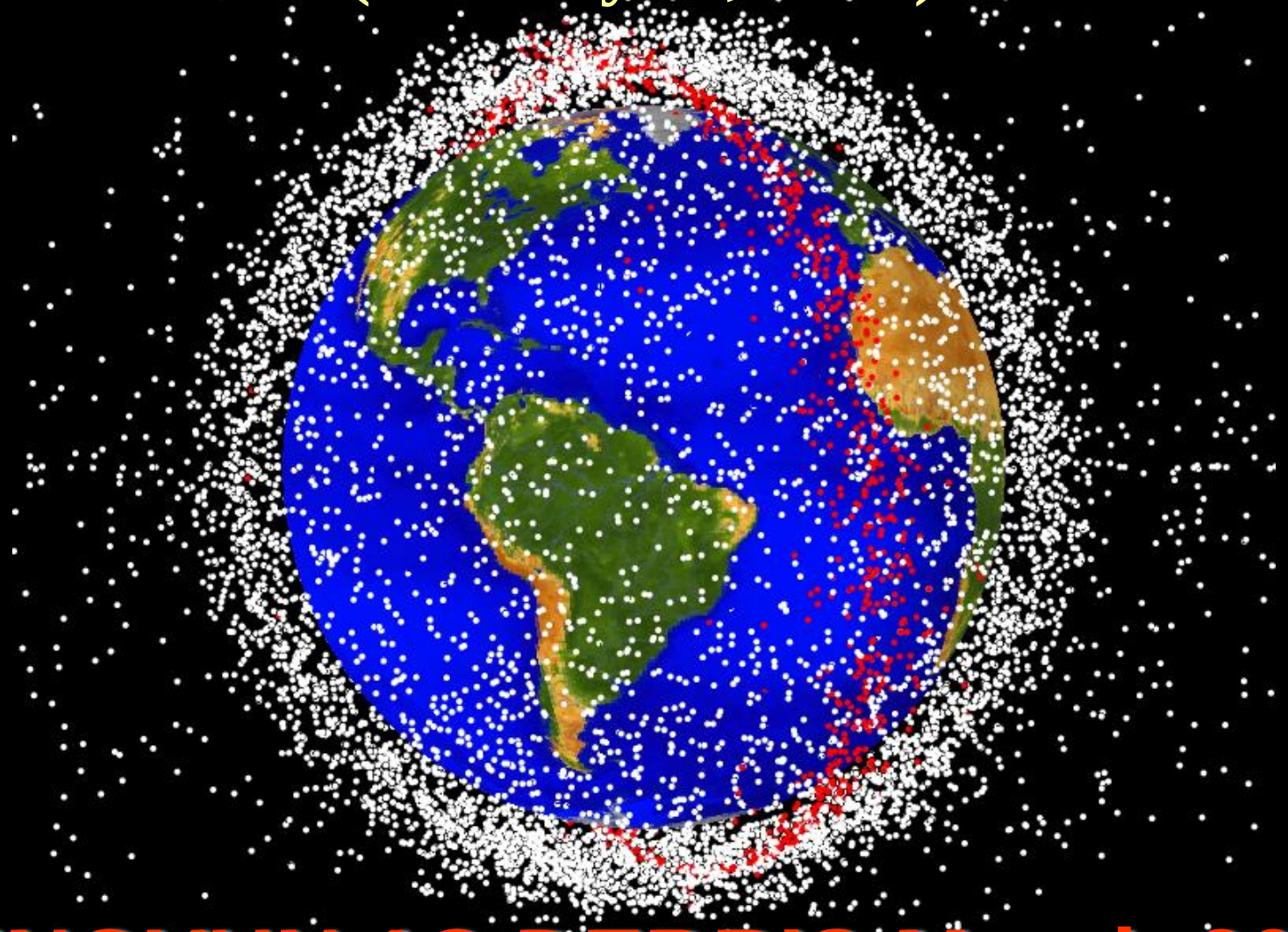
Terra normally maneuvers a few times each year to maintain its precision orbit, and the collision avoidance maneuver was designed to serve this same function to prevent the waste of precious propellant. A very small maneuver was performed nearly two days before the anticipated encounter, ensuring that 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. ♦

Early EOS Conjunction Assessment Experience (2006 and 2007)

Primary	Secondary	TCA	Comments
Terra	1716	12-Jan-06	**Waived-off planned routine drag make-up maneuver**
Aura	4519	14-Jan-06	
Aura	3048	10-Feb-06	
Aqua	3048	20-Apr-06	
Aqua	7338	12-Oct-06	
Aura	17649	19-Apr-07	
Terra	4579	15-May-07	
Terra	82441	25-May-07	
Aqua	82317	1-Jun-07	
Terra	31410	23-Jun-07	**Second NASA Robotic Mission Debris Avoidance Maneuver (DAM)**
Aura	25450	15-Jul-07	
Aqua	31496	17-Aug-07	**Insufficient information to warrant a maneuver**
Aqua	30821	29-Sep-07	
Aura	81134	29-Oct-07	
Terra	11113	22-Nov-07	

Terra (5), Aqua (5), Aura (5) – TOTAL 15

Chinese ASAT Destruction of Fengyun-1C (January 11, 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

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

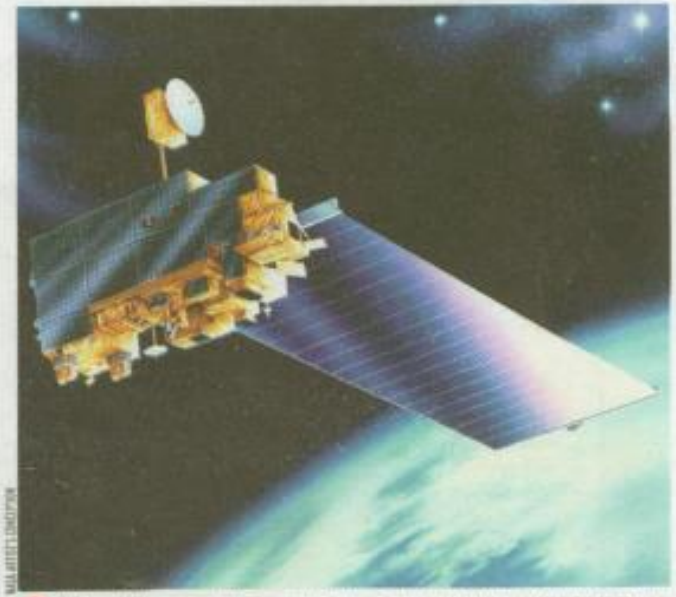
BRIAN BERGER, WASHINGTON

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 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

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

National Aeronautics and Space Administration

Orbital Debris Quarterly News

Volume 11, Issue 3
July 2007

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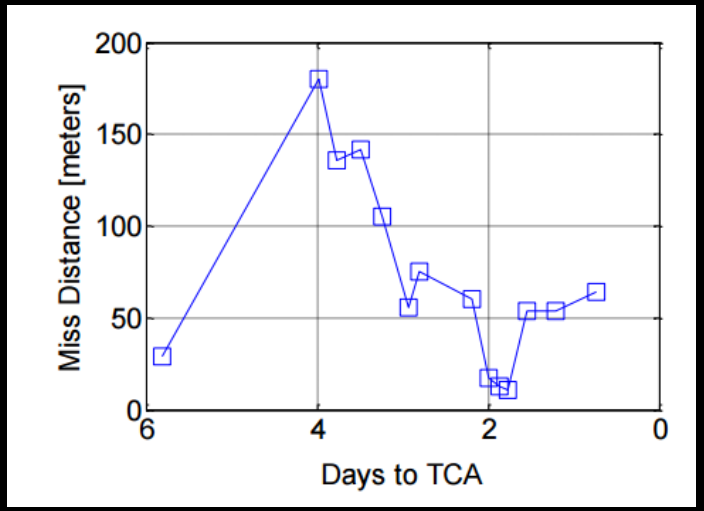
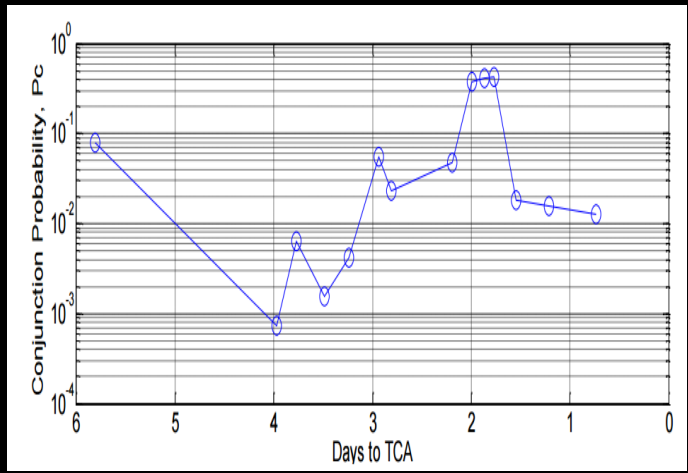
The large number of debris from Fengyun-1C are posing greater collision risks for spacecraft operating in low Earth orbit. The number of close approaches has risen significantly. On 22 June, NASA's Terra spacecraft had to execute a collision avoidance maneuver to evade a fragment from Fengyun-1C that 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 → about 500 meters
  - Pc → 0





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

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

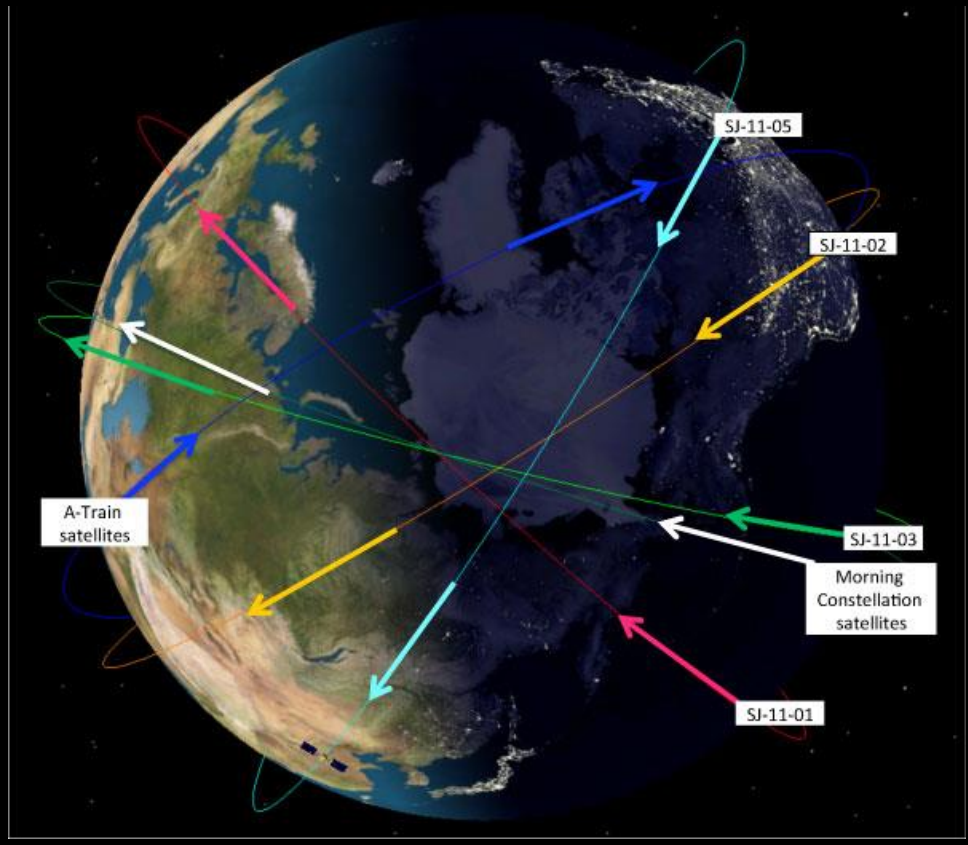
- **1st EOS Aqua DAM**
  - **November 25, 2009**
  - **Peak Pc of about 1:14**
  - **Minimum miss distance of about 25 meters**
  - **Mitigated by 1.25 sec mini-drag make-up maneuver**
  - **Burn at TCA minus 24-hours**
  - **Miss Distance → about 560 meters**
  - **Pc → 0**

Maneuver options limited due to routine drag make up maneuver performed 8-days prior to TCA

CREDIT: NASA Robotic Mission CARA Team

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.



CREDIT: EOS Flight Dynamics Team

- 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

	Primary	Secondary Object Number	Secondary Description	Maneuver Date	Time of Closest Approach (GMT)	Minimum Miss Distance (m)	Maximum Pc
1	Terra	14222	SCOUT G-1	21 Oct 2005	2005 Oct 23 20:53:28	37	8.15E-02
2	Terra	31410	Fengyun 1C Debris	22 Jun 2007	2007 Jun 23 21:44:00	18	1.58E-01
3	Aura	1399	TRIAD 1 Debris	26 Jun 2008	2008 Jun 27 15:34:00	11	4.80E-01
4	Aqua	30420	Fengyun 1C Debris	25 Nov 2009	2009 Nov 26 15:36:57	25	7.01E-02
5	Terra	34700	Iridium 33 Debris	22 Jan 2010	2010 Jan 23 20:46:55	244	5.74E-03
6	Aura	30262	Cosmos 2251 Debris	22 Nov 2010	2010 Nov 24 11:16:52	50	3.90E-02
7	Aqua	35957	Cosmos 2251 Debris	02 Jan 2011	2011 Jan 05 18:17:23	94	8.40E-03
8	Aqua	34494	Iridium 33 Debris	08 Feb 2011	2011 Feb 08 19:32:28	41	4.70E-02
9	Aqua	4917	Thorad Agena D Debris	01 Mar 2011	2011 Mar 02 02:45:09	204	3.40E-03
10	Aura	34574	Cosmos 2251 Debris	16 May 2012	2012 May 17 19:09:17	81	4.70E-04
11	Aqua	407	Thor Ablestar Debris	10 Mar 2013	2013 Mar 12 04:02:53	860	2.57E-03
12	Aqua	35733	Iridium 33 Debris	23 Mar 2013	2013 Mar 24 00:30:17	84	2.40E-02
13	Terra	12343	Cosmos 1174 Debris	24 Mar 2013	2013 Mar 26 04:24:18	113	2.38E-03
14	Terra	26209	CZ-4 Debris	18 Aug 2013	2013 Aug 19 07:43:02	79	6.72E-02
15	Aura	37765	SJ-11-02	02 Sep 2013	2013 Sep 03 04:02:44	320	2.23E-04
16	Aqua	34510	Iridium 33 Debris	25 Oct 2013	2013 Oct 25 04:27:48	689	8.99E-04
17	Terra	31201	Fengyun 1C Debris	17 Nov 2013	2013 Nov 18 05:42:16	272	1.01E-02
18	Aqua	35652	Cosmos 2251 Debris	28 Nov 2013	2013 Nov 28 22:28:03	373	6.41E-04
19	Terra	26347	CZ-4 Debris	10 Feb 2014	2014 Feb 10 11:52:32	152	1.24E-02
20	Terra	9040	Delta 1 Debris	21 Mar 2014	2014 Mar 23 00:17:43	50	2.35E-03
21	Aura	36712	Fengyun 1C Debris	29 Aug 2014	2014 Sep 02 12:32:48	408	1.19E-03
22	Aqua	81180	UNKNOWN	21 Oct 2014	2014 Oct 21 04:17:27	4935	6.90E-04
23	Terra	35925	Iridium 33 Debris	31 Dec 2014	2015 Jan 01 06:24:00	206	9.67E-04

CREDIT: NASA Robotic Mission CARA Team

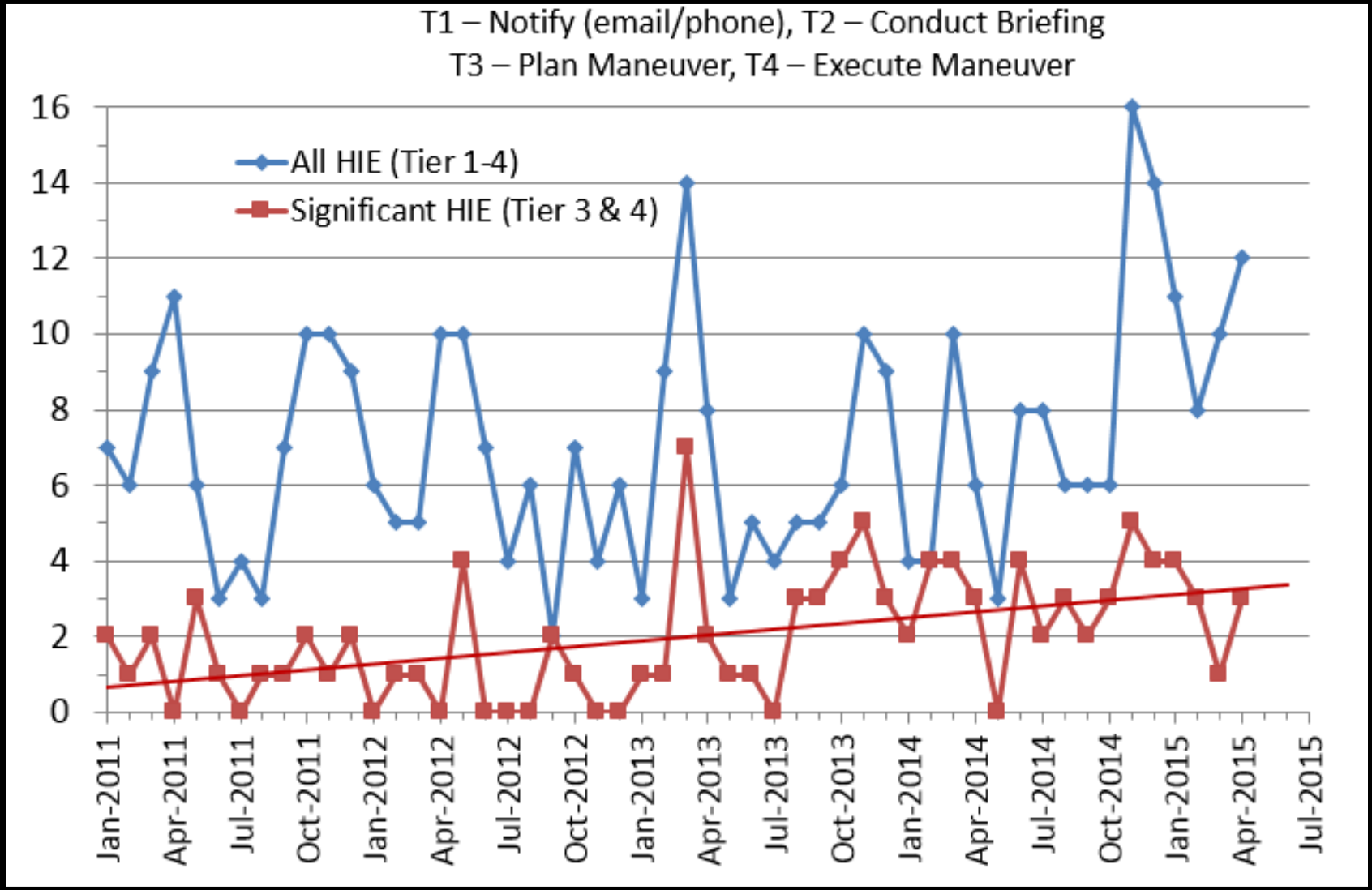
EOS Maneuvers Postponed or Re-planned (2005 – 2014)

	Primary	Secondary Object Number	Secondary Description	Maneuver Mitigation	Maneuver Date	Time of Closest Approach (GMT)	Minimum Miss Distance (m)	Maximum Pc
1	Terra	1716	Titan 3C Transtage Debris	Postpone	UNK	2006 Jan 12 17:46:17	334	0.00E+00
2	Aura	2799	Titan 3C Transtage Debris	Postpone	17 Jun 2008	2008 Jun 13 03:26:59	5671	N/A
3	Aura	28297	DMSP 5D-2 F11 debris	Postpone	17 Jun 2008	2008 Jun 15 20:34:51	7340	N/A
4	Aqua	29107	CloudSat	Replan	08 Jun 2011	2011 May 22 00:00:00	UNK	N/A
5	Aqua	33640	Fengyun 1-C debris	Replan	23 Jun 2011	2011 Jun 23 17:27:17	65.9	4.92E-02
6	Aqua	34429	Cosmos 2251 Debris	Postpone	25 Aug 2011	2011 Aug 29 03:57:45	30739	0.00E+00
7	Aura	34002	Cosmos 2251 Debris	Replan	08 Sep 2011	2011 Sep 03 05:57:41	50.4	2.20E-03
8	Aqua	26313	CZ-4 Debris	Replan	25 Oct 2011	2011 Oct 26 11:13:57	1349	1.80E-03
9	Aqua	2799	Titan 3C Transtage Debris	Postpone/Replan	20 Dec 2011	2011 Dec 16 19:36:36	45775	0.00E+00
10	Terra	37789	Nigeriasat-2	Postpone	31 May 2012	2012 Jun 01 22:49:38	19970	0.00E+00
11	Aura	87438	AnalystSat	Postpone	29 Aug 2012	2012 Sep 02 13:28:57	63	2.74E-03
12	Aqua	30984	Fengyun 1-C debris	Replan	13 Sep 2012	2012 Sep 16 06:50:39	63005	0.00E+00
13	Aqua	34442	Cosmos 2251 Debris	Replan	25 Jan 2013	2013 Jan 28 19:46:57	190	3.23E-04
14	Aura	27606	Latinsat B	Postpone	03 Apr 2013	2013 Mar 24 22:04:30	5096	7.28E-16
15	Aura	22409	SL-16 Debris	Postpone	03 Apr 2013	2013 Mar 30 03:08:00	20095	3.24E-103
16	Aqua	27123	PSLV Debris	Postpone	30 Apr 2013	2013 Apr 24 07:44:05	3810	6.63E-08
17	Aura	35469	Cosmos 2251 Debris	Replan	15 Nov 2013	2013 Nov 18 17:50:39	157	1.27E-02
18	Aqua	22481	SL-16 Debris	Postpone	14 Jan 2014	2014 Jan 09 23:30:54	3355	2.50E-05
19	Aqua	37538	Cosmos 2251 Debris	Postpone	14 Jan 2014	2014 Jan 14 17:24:52	2930	4.06E-06
20	Terra	20281	Magion 2	Postpone	26 Feb 2014	2014 Feb 26 02:42:38	6806	1.14E-06
21	Aura	34327	Cosmos 2251 Debris	Replan	19 Jun 2014	2014 Jun 20 05:22:29	137	3.11E-03
22	Terra	37343	Cosmos 2251 Debris	Postpone	13 Nov 2014	2014 Nov 08 22:46:45	6067	0.00E+00
23	Terra	35050	Iridium 33 Debris	Replan	12 Dec 2014	2014 Dec 13 15:44:41	4320	2.13E-04
24	Aura	30085	Fengyun 1-C debris	Postpone	28 Jan 2015	2015 Jan 24 13:34:36	1460	6.82E-04

As much or more effort as RMMs/DAMs

CREDIT: NASA Robotic Mission CARA Team

EOS Debris Avoidance Activities (January 2011 – April 2015)



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

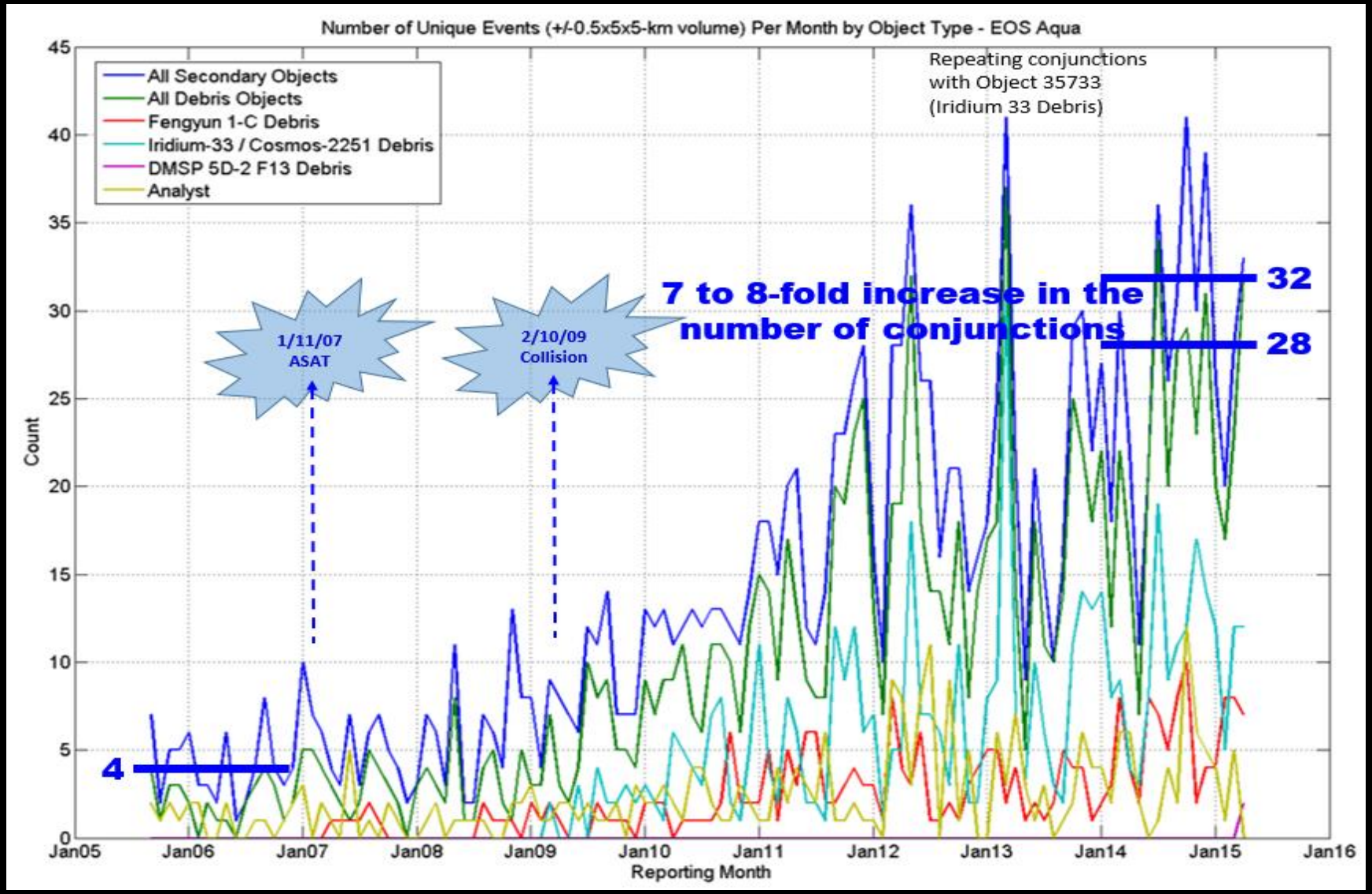
2014: 91 HIEs – 10 DARMs – 36 HIEs required significant effort

- 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

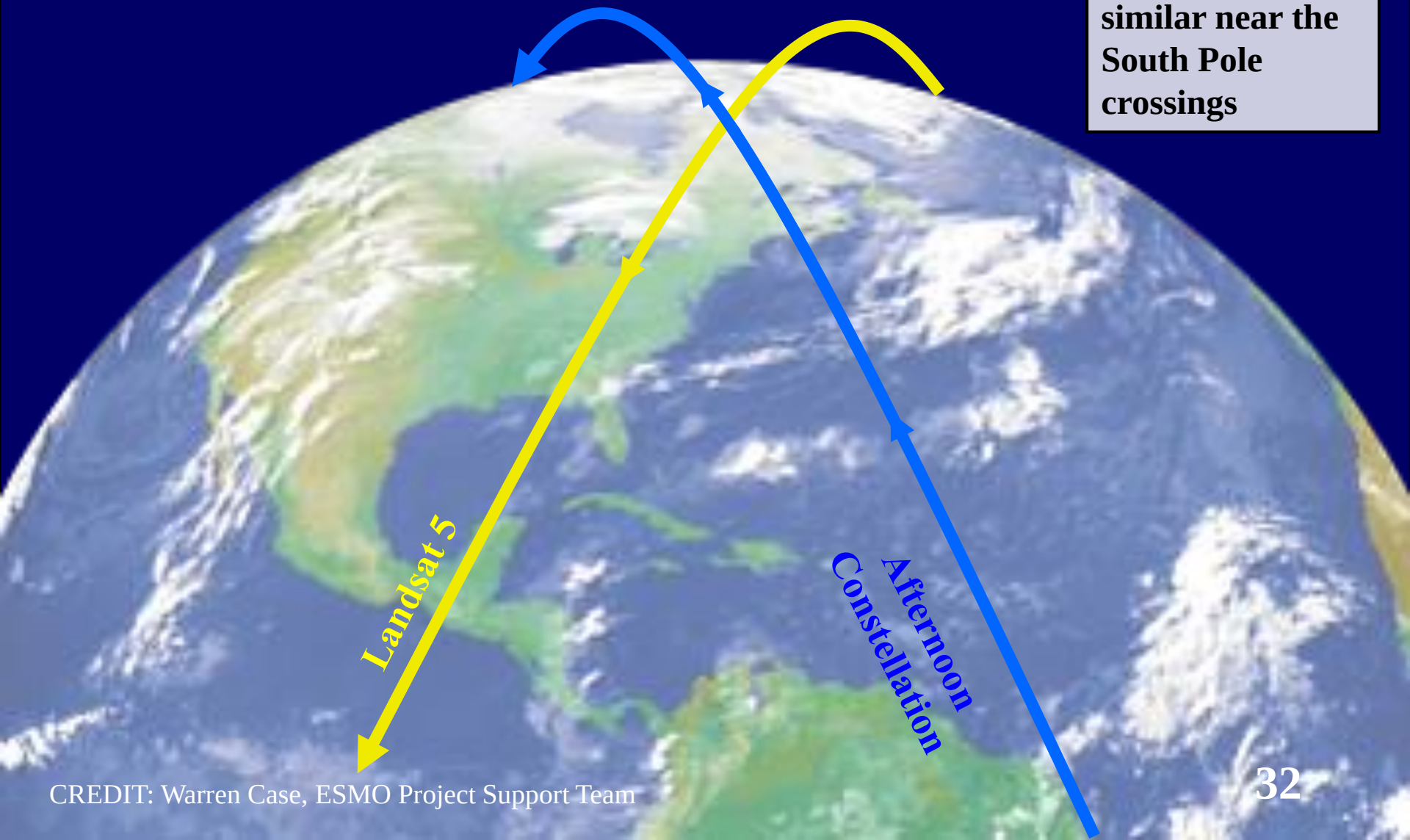
A-Train Systematic Conjunctions

A-Train
Afternoon Constellation
Systematic Conjunctions

Landsat 5 Crossing through the Afternoon Constellation (A-Train)

(Start slide show to view animation)

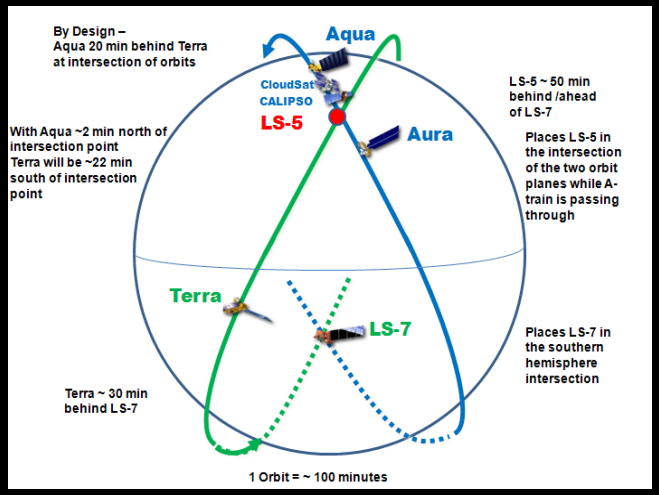
Situation is similar near the South Pole crossings

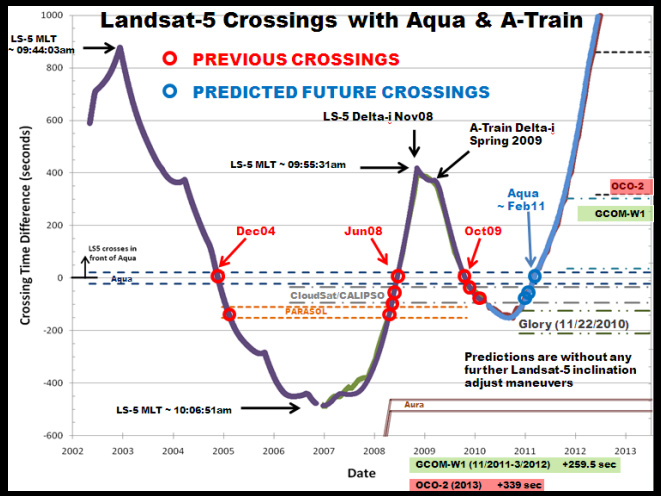


CREDIT: Warren Case, ESMO Project Support Team

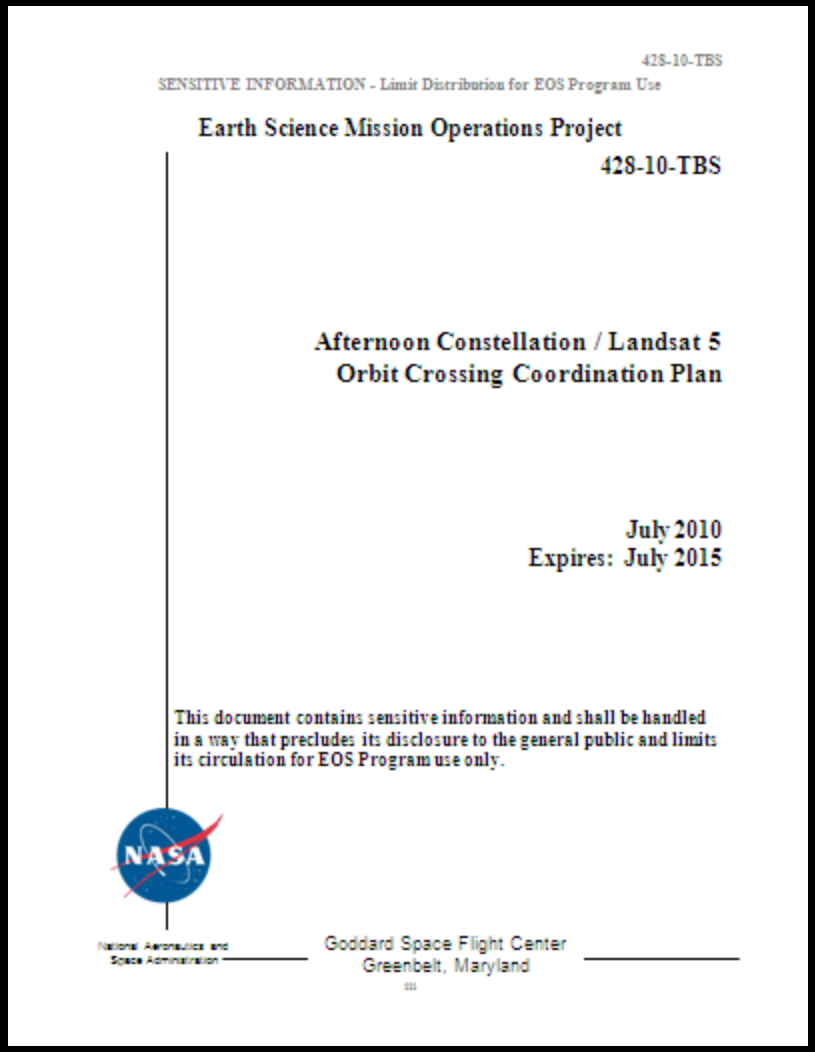
Landsat-5 Conjunctions with the A-Train (Afternoon Constellation)

- 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)



428-10-TBS

SENSITIVE INFORMATION - Limit Distribution for EOS Program Use

Earth Science Mission Operations Project

428-10-TBS

Afternoon Constellation / Landsat 5
Orbit Crossing Coordination Plan

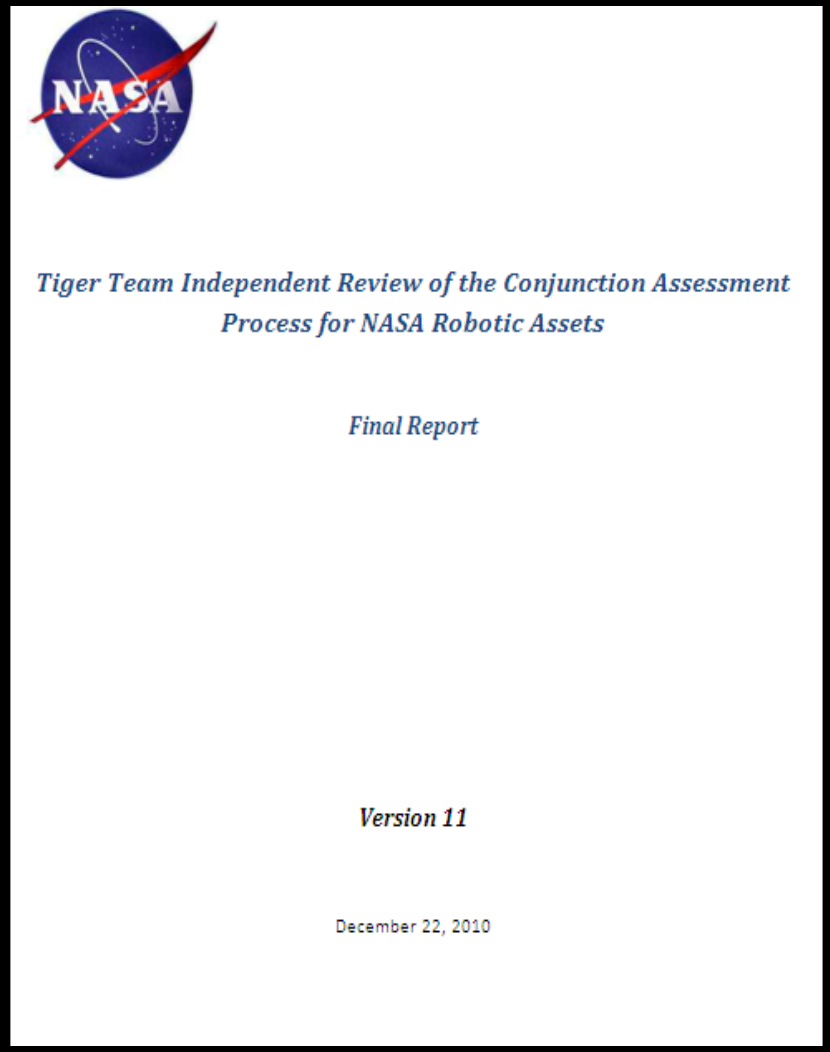
July 2010
Expires: July 2015

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.

National Aeronautics and Space Administration

Goddard Space Flight Center
Greenbelt, Maryland

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

AAS/AIAA Astrodynamics Specialist Conference
Girdwood, Alaska
August 2011
Session 15
Satellite Constellations

AAS 11-544

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.

AIAA Space Ops 2012
12th International Conference on Space Operations
Stockholm, Sweden
June 2012
AIAA 2012-1274816

Operational Collision Risk Assessment of CALIPSO and LANDSAT-5 Crossings

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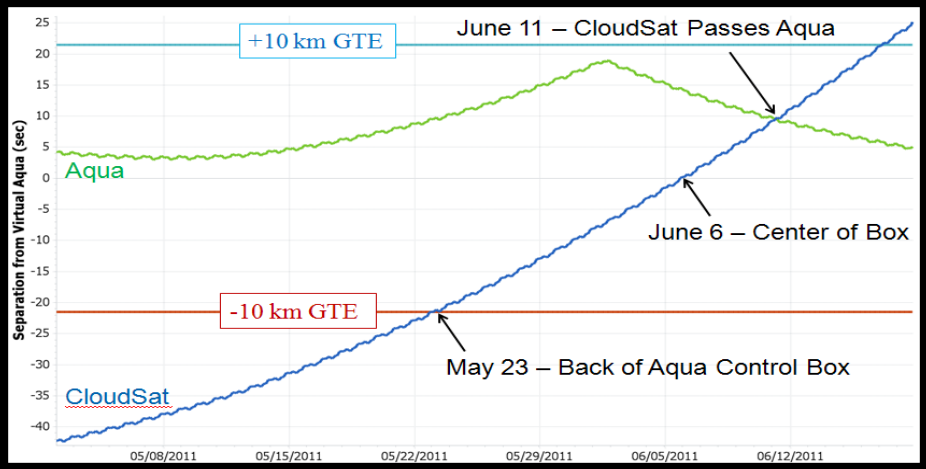
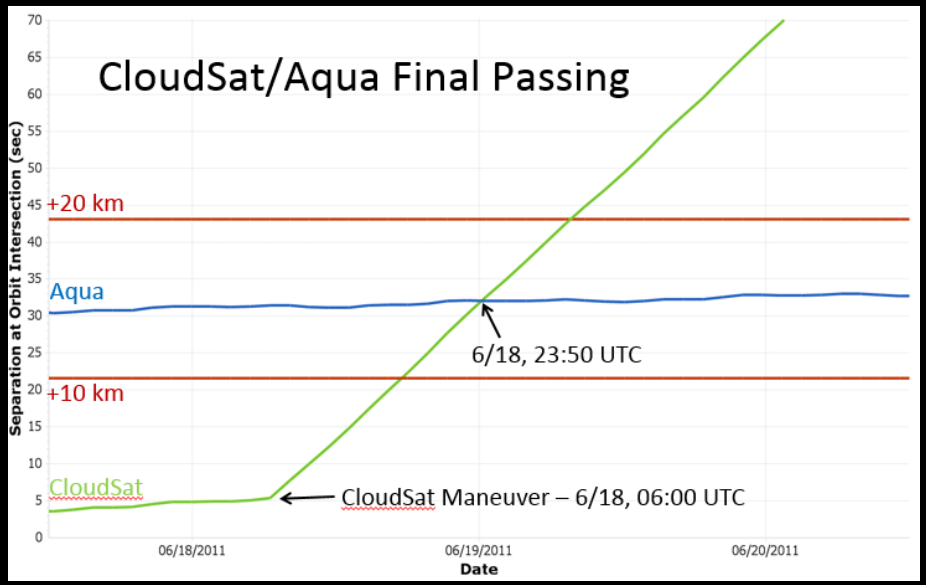
In late February 2010 the French Space Agency (Centre National d'Etudes Spatiales, CNES) and NASA (LaRC, Langley Research Center) operations teams in charge of the CALIPSO satellite were notified of an unfavorable spacecraft collision risk with the Landsat-5 satellite detected by the NASA Earth Science Mission Operations (ESMO) team. As a member of the Afternoon Constellation, CALIPSO is orbiting in a sun-synchronous frozen orbit following a repetitive ground track at a mean equatorial altitude of 705 km. Landsat-5, operated by the United States Geological Survey (USGS), is also orbiting in a sun-synchronous frozen orbit following almost the same ground track at the same mean equatorial altitude. Both orbits can be considered as nearly identical, the main difference between them being the mean local time of the ascending node. The assumed in orbit position difference between the two satellites was such that the relative phasing should not create any collision risk despite the orbit intersections. However, changes in mean local time of Landsat-5 and the Afternoon Constellation modified the orbital configuration and led to dangerous crossings during a significant period of time. This issue concerns not only CALIPSO and Landsat-5, but also all the current and future Afternoon Constellation missions. This paper will introduce the station keeping principles that led to the dangerous orbital configuration and the flight dynamics aspects taken into account to study the crossings. It will continue to present the CNES and LaRC tools developed to identify the crossings and to compute the maneuver trade space permitting to choose the maneuver parameters that mitigate the collision risk. Finally, it will describe the maneuver strategy agreed upon by all the concerned missions to manage the close approaches.

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)



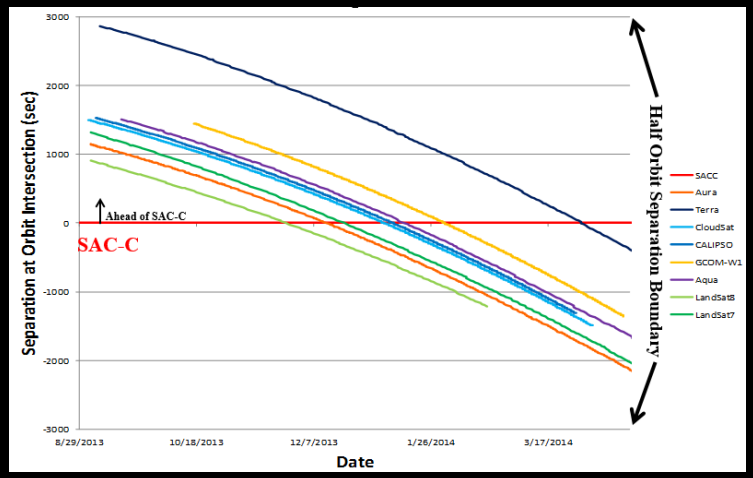


CREDIT: EOS Flight Dynamics Team

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**

Spacecraft	Estimated Crossing Date	Radial Separation (km)
LandSat-8	Nov. 25, 2013	-4 to -2
Aura	Dec. 11, 2013	-1.3 to -0.3
LandSat-7	Dec. 20, 2013	-15
CloudSat	Jan. 5, 2014	-0.8 to 0
CALIPSO	Jan. 9, 2014	-1 to 0
Aqua	Jan. 14, 2014	-1 to 0
GCOM-W1	Jan 31, 2014	-0.7 to 0.8
Terra	Mar. 30, 2014	0.5 to 1.5

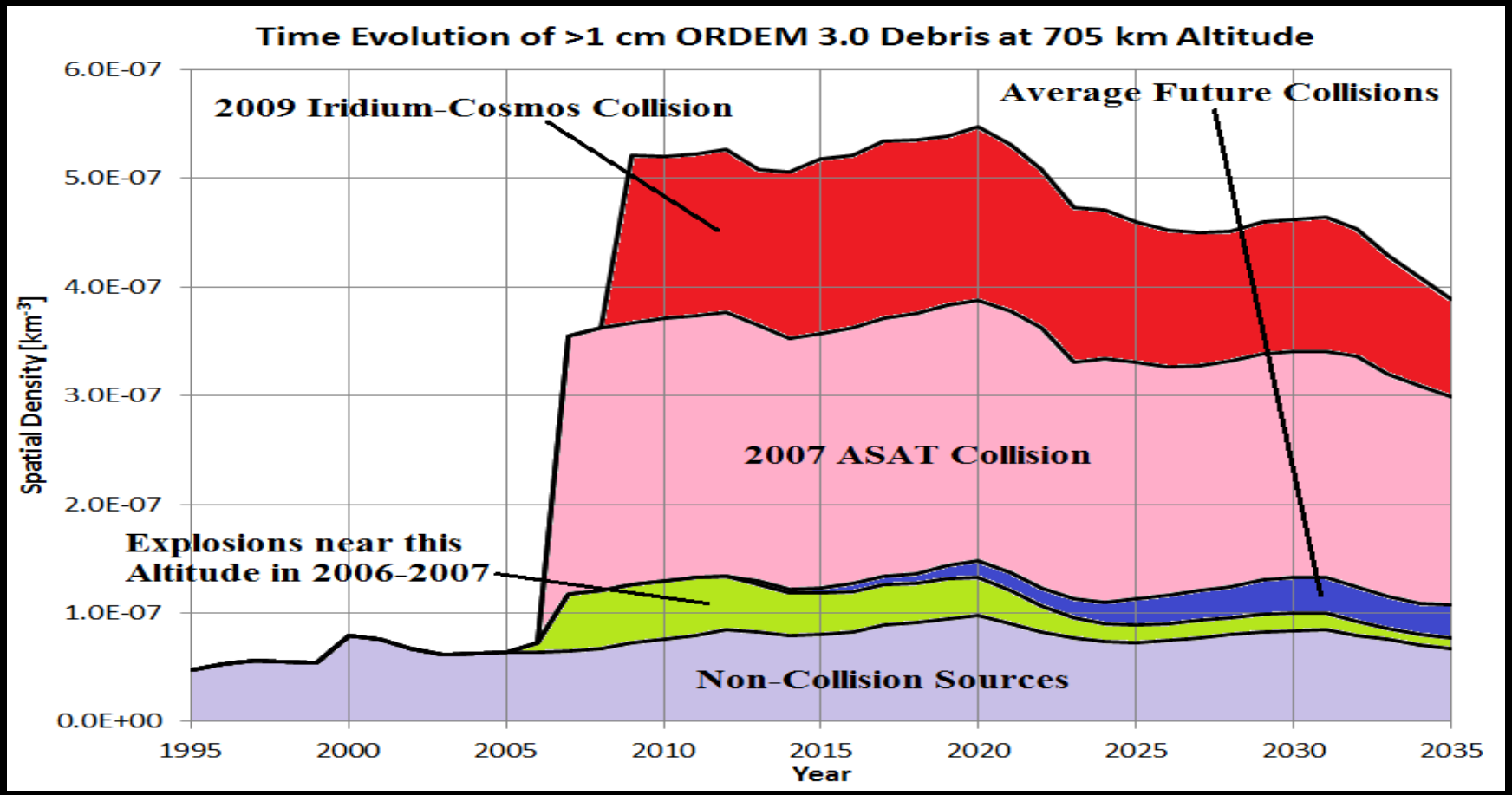


CREDIT: EOS Flight Dynamics Team

Future Challenges

Debris Population Projected to get Worse

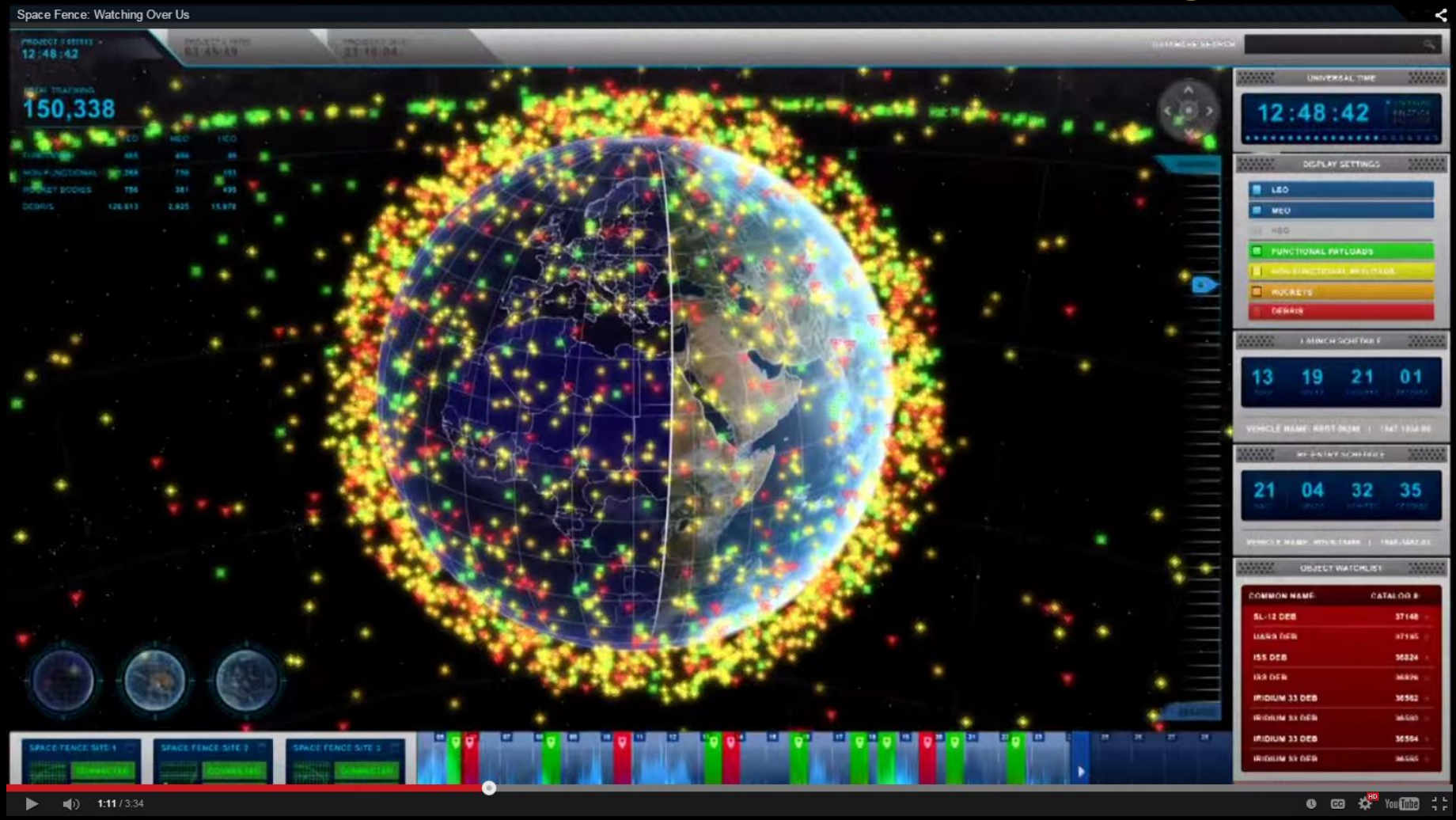
Note: Five-fold increase from 2005 to 2010



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.**
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

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 ***

Earth Science Mission Operations Orbital Safety (2014)

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 705 km. Sensors/instruments were provided by U.S., Japan, United Kingdom, Canada, France, The Netherlands and Brazil.

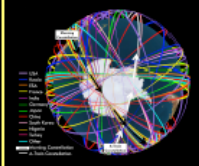
- Morning Constellation: cross the equator between of 10:00 a.m. - 10:45 a.m Mean Local Time (MLT).
- Afternoon Constellation (known as the A-Train): cross the equator between 1:30 p.m. - 1:45 p.m. MLT.

Space Objects

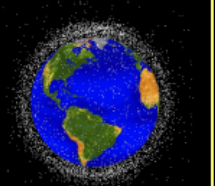
Maneuverable Satellites
- Satellites that change their orbit periodically, usually to maintain their required orbital location
- As needed, satellites maneuver to avoid a close approach with other space objects

Non-Maneuverable Satellites
- Some active satellites lacking propulsion systems
- Satellites out of fuel

Non-maneuverable Objects
- Orbital debris (estimated: 500,000 between 1 and 10 cm, 100 million less than 1 cm)



Satellites Near 705 Km Constellation Orbits



Orbital Debris in Low Earth Orbits
(Source: http://orbitaldebris.jsc.nasa.gov)

Coordination To Ensure Safety

If a maneuverable satellite is predicted to come close to a piece of orbital debris or a non-maneuverable satellite, it must change its orbit to avoid a collision.

If a maneuverable satellite is predicted to come close to another maneuverable satellite, the two mission teams must coordinate their actions to ensure that the two satellites do not both maneuver in ways that increase (rather than decrease) the collision risk. This coordination must be done in a timely manner.

NASA's Approach to Satellite Safety

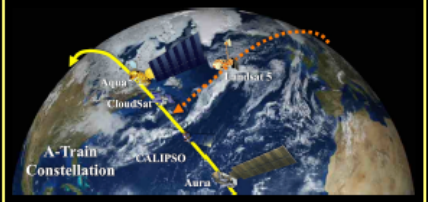
- Constellation satellites maintain their location to satisfy science requirements
- Monitoring is performed to ensure safety
  1. Conjunction Assessment Risk Analysis (CARA) Team
     - Monitors all NASA satellites and related constellation satellites
     - Notifies the affected mission team if a potential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

- If needed, the satellite operators perform risk mitigation maneuvers

Satellite Safety Web Site

- Promotes safety
- Facilitates communications between satellite operators
- Provides information to other satellite operators about NASA and constellation missions:
  a. Constellation mission descriptions (including maneuver capabilities)
  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

Case History: A-Train and Landsat 5



- In 2010, Landsat 5 crossed through the A-Train orbit 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 705 km orbit safe.

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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