Conjunction Assessment Risk Analysis

CARA Status and Upcoming Enhancements

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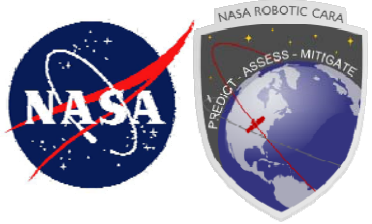
With contributions from the CARA Team

Spring 2015 A-Train Mission Operations Working Group (MOWG)

3June 2015

Agenda

- **CARA Operational Highlights**
- **CARA Service Enhancements**
  - CAS 8.1 Release Content
  - Maneuver Trade Space (MTS) 2.0
  - Screening Volume Analysis
  - FSO Template Update
  - Upcoming software release
- **Special Topics**
  - DMSP F13 Breakup
  - Discussion of “surprise” events
  - Ephemeris Naming Convention
- **CARA Statistics**
- **Questions and Discussion**

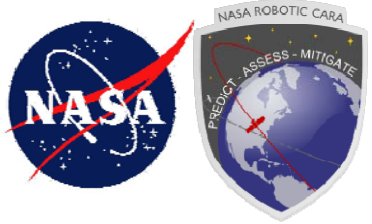


CARA OPERATIONAL HIGHLIGHTS

CARA Operational Highlights

- **Mission-specific HBR updates**
  - CloudSat updated to 3.5 m
  - Landsat 8 updated to 9.0 m
- **SMAP launch**
  - January 31 launch
  - 685-km sun-synchronous orbit
  - No RMM planning (through March)
- **MMS launch**
  - March 12 launch
  - 4 satellites in HEO constellation
- **TRMM end-of-life support**
  - CARA supported fuel depletion burn campaign in March
  - CARA will continue screening until mission decides to halt services
  - Passivation occurred 15 APR

Mission	HBR (m)
Aqua	20
Aura	20
CALIPSO	15.7
CloudSat	3.5
GCOM-W1	20
Landsat 7	20
Landsat 8	9
OCO-2	6
Terra	20



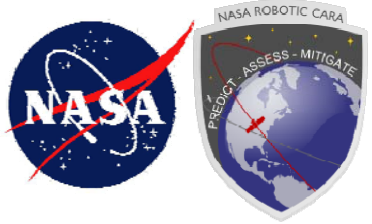
CARA SERVICE ENHANCEMENTS

CAS 8.1 Overview

- **Promoted to operations on April 14**
  - No interruptions to report delivery or other CARA services
- **The release was designed to be a shorter release containing:**
  - Updates needed to support the MMS mission
  - Request by NASA HQ
  - Bug fixes identified during last release feedback discussions
  - Summary Report updates and enhancements

8.1 Content : Summary Report

- **RIC Miss Values in Summary Table**
  - Tabular presentation of miss vector in Summary Section
- **RIC Uncertainty Values in Details Section**
  - Numerical presentation of miss component uncertainty values in Details Section
- **Green Events with Potentially Maneuverable Secondary Objects**
  - All potentially maneuverable secondary objects will be reported out to 7-days prior to TCA for LEO events and 10-days for NONLEO events, regardless of risk (relates to MOWG Action Item 1309-11)
  - All green events with potentially active secondary objects included in Summary Reports
  - Allows more time for contacting other O/O
- **Black Box Fix**
  - Sometimes a black square appeared in the summary report where the ASW RIC time history plot should be
- **Appendix Orbit Regime/Mission Name Mismatch**
- **Pc 0 Plotting Bug**
  - All Pc points less than 1e-10 (“zero”) are now plotted as 1e-10 (instead of not at all)
- **Maneuver Indication Fix**
  - Maneuver indicator now present even if maneuver was in the past



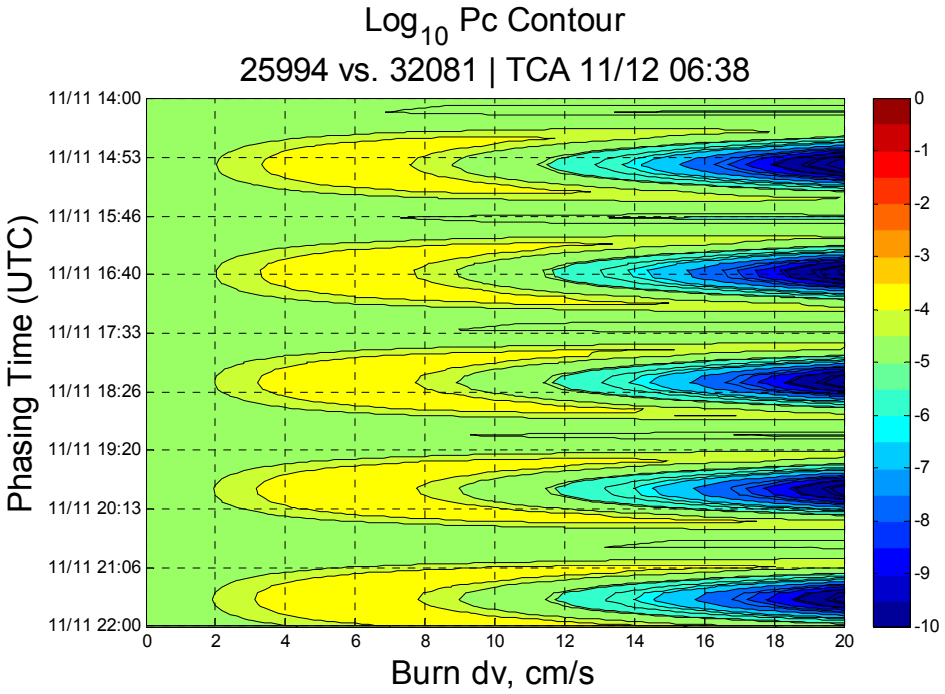
MANEUVER TRADE SPACE 2.0

Motivation / Requirements for MTS 2.0

- **Total Pc plots for multiple / repeating conjunction situations**
  - Address immediate need for this information in maneuver planning
  - Path-finder for finite CA approach of remediating groups of conjunctions rather than single events
  - *Also produce traditional Pc and miss-distance plots for each individual event in multiple/repeating situation*
- **Chemical burn and electric propulsion situations addressed**
  - Framework to accommodate differential drag situation
- **Adequate output grid resolution to enable full exploitation by CARA and owner/operators**
- **Sufficiently rapid execution time to allow all operational objectives to be met**
- **ASW and owner/operator accepted as inputs**

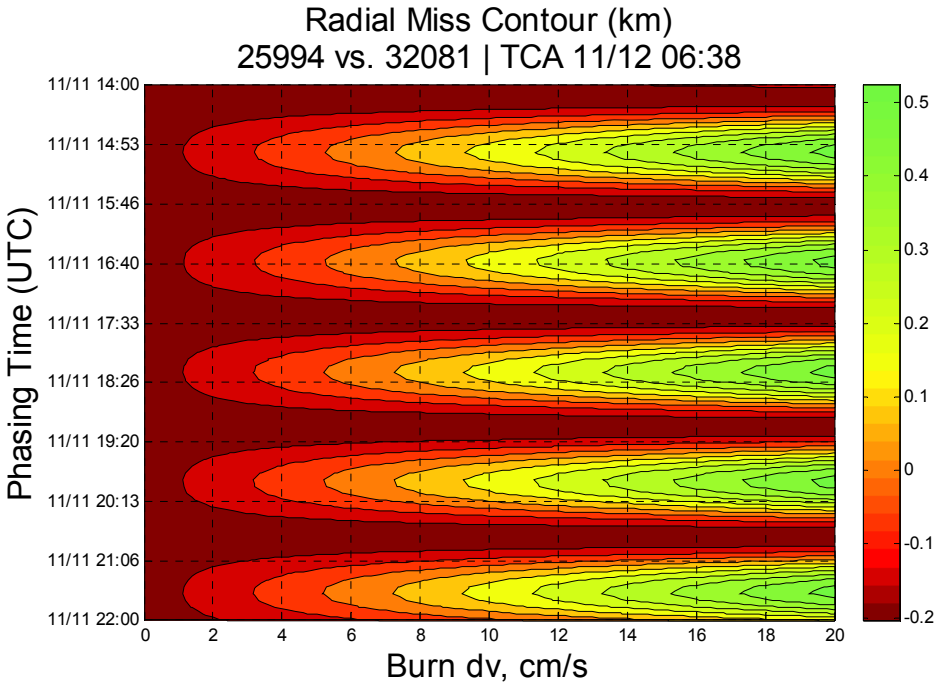
Chemical Burn Outputs

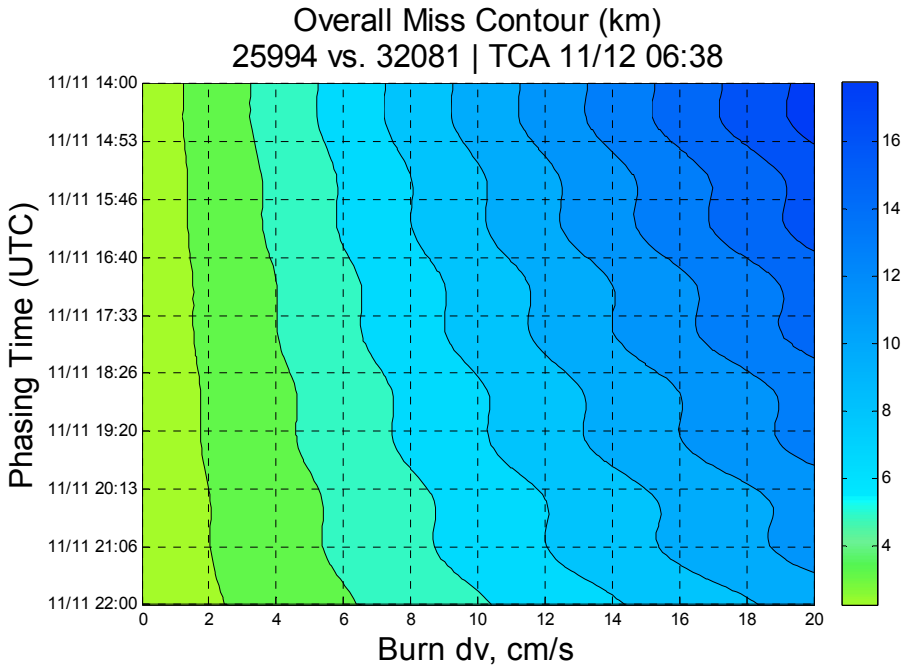
- **Outputs available for each discrete conjunction**
  - Miss distance and probability saved as figures and data
- **Output for total risk also saved as plots and data**
  - $TPc = 1 - \prod_{i=1}^{n}(1 - Pc_i)$



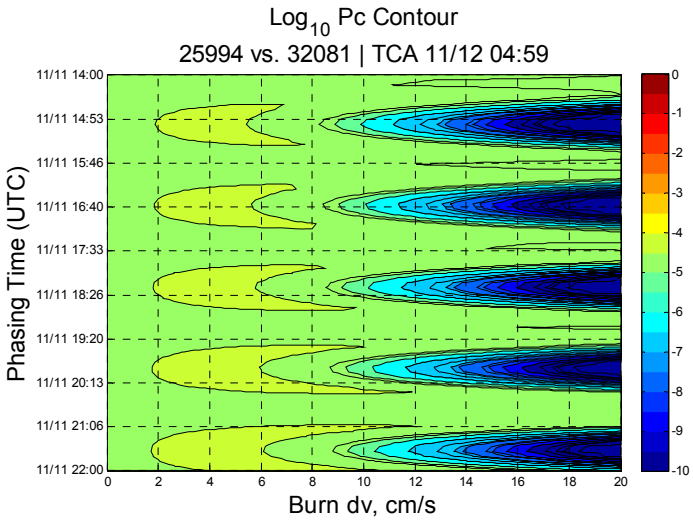
Chemical Burn Outputs: RIC Miss Distance

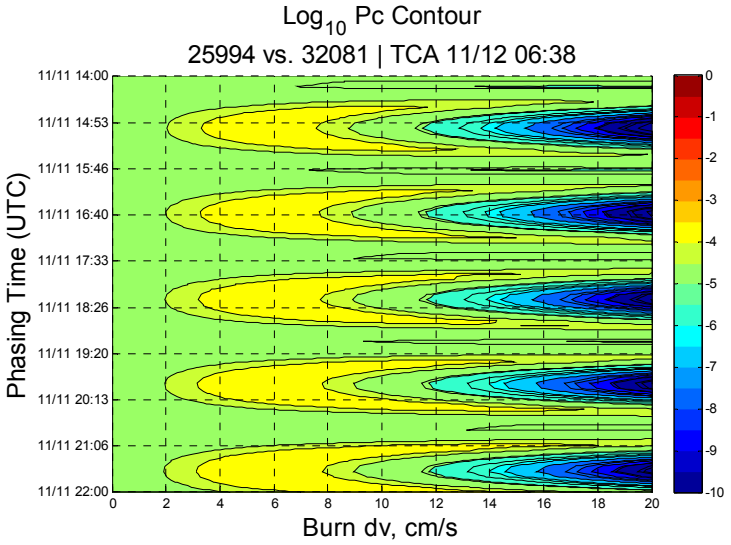
- **Miss distance plots are saved for each discrete conjunction**
  - Plots indicate the satellite numbers and the TCA time
  - Total Pc plot lists the primary satellite number



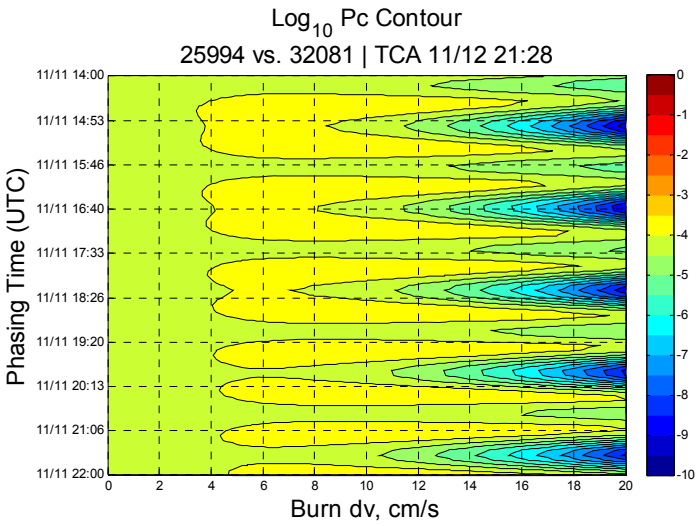


Chemical Burn Outputs: Total Probability Example

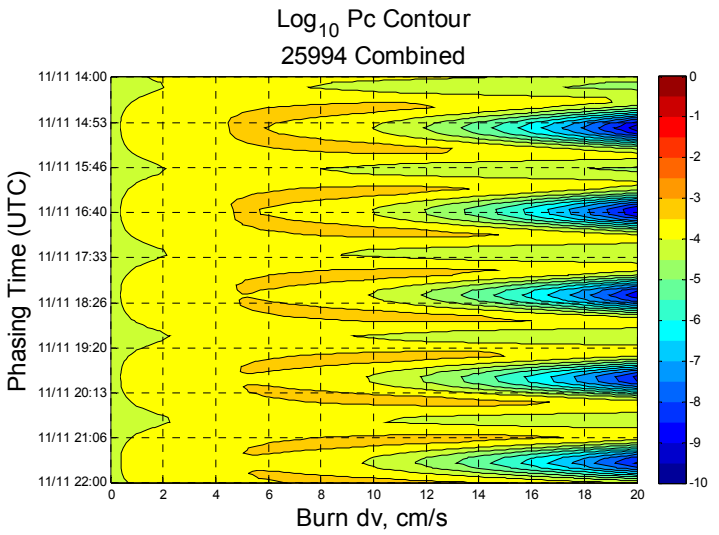




Three Individual Events

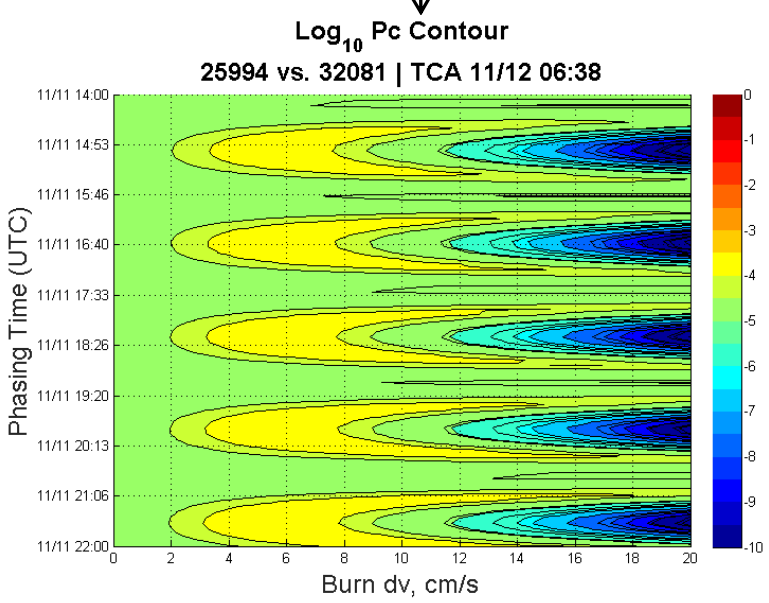


Total Pc

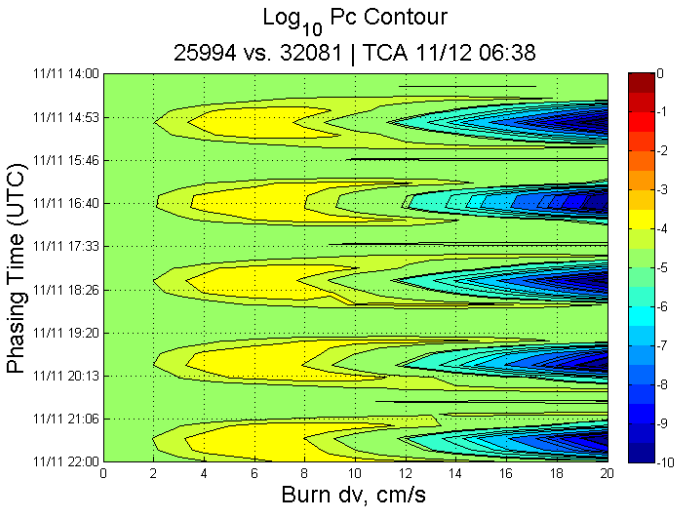


Chemical Burn Outputs: Grid Resolution

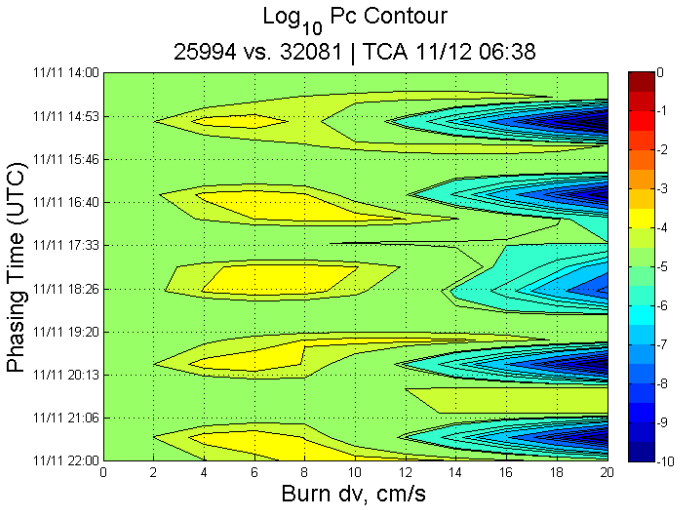
High Resolution
Interval 6 min
Step 0.2 cm/s



15 min
1 cm/s

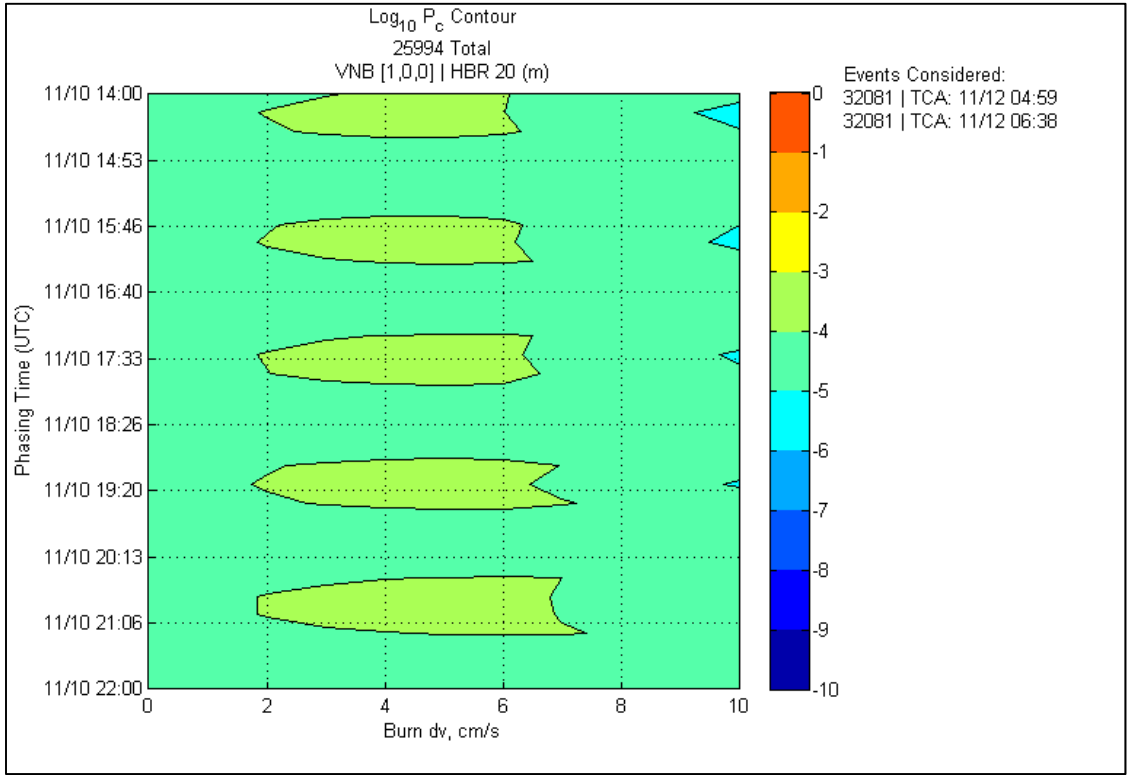


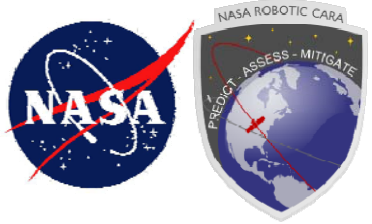
30 min
2 cm/s



MTS 2.1

- **Planned enhancements (relevant to MOWG)**
  - Performance improvements
  - Events considered annotation
  - O/O Ephemeris as input
  - Differential drag “maneuver” type
- **Promotion to operations should occur in next week or two**
- **Targeting integration into CAS system and automation by end of year**
  - Desire is to have as standard feature on daily Summary Reports



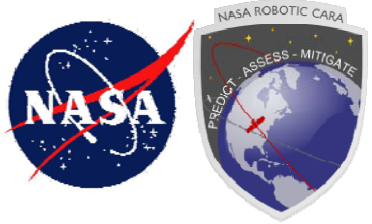


SCREENING VOLUME ANALYSIS

Screening Volume Analysis

- **CARA performs annual analysis to resize screening volumes**
  - 2015 analysis underway now
- **CARA is undertaking a new approach to determining volume size using Monte Carlo analysis**
- **Analysis expected to complete late Spring / early Summer**
  - Users Forum on approach and results will be conducted

FOREIGN SATELLITE OPERATOR (FSO) COMMUNICATION TEMPLATE



FSO Template Status: Background

- **In Fall 2013, we identified a need to have a standard template for communicating with International Satellite Owner/Operators**
  - Include close approach *and* risk assessment information
  - Include contextual information under which the risk assessment is applicable
  - Include NASA course of action
  - Include request for information
- **CARA to work template, process, and approvals**
- **MOWG Action Items 1309-09 and 1309-10**

- **Status Overview: Process and procedures are in place to produce a message with the NASA O/O using the FSO template and send to HQ/SMD for approval to contact the FSO**
- **This process has been used successfully to support several conjunctions, but routing of message depends on NASA relationship/existing agreements with the FSO**

FSO Template Status: Activity since last MOWG [1 of 2]

- **Apr 15, 2014: FSO template sent to NASA Office of Interagency and International Relations (OIIR)/John Hall**
- **Jun 23, 2014: John Hall approved draft template**
- **Jul 10, 2014: Orbital Data Request (ODR) sent to JSpOC to request permission to redistribute their data as part of the FSO template**
  - Request not yet approved
- **Nov 2014: State received an email address for China BITTT**
  - JSpOC begins using this email to send emergency notifications to China
- **Dec 2014: Had telecon with HQ, State, OSD(P), JSpOC, and STRAT to determine how NASA can send the template to China.**
  - **State preferred to be removed from the loop**
  - **JSpOC said it was operationally feasible to send NASA's FSO template message**
  - **Following the telecon, OSD (P) came to the decision that the correct authorities do not exist to allow JSpOC to perform this function on NASA's behalf**

FSO Template Status: Activity since last MOWG [2 of 2]

- **Mar 2015: Had follow-up telecon with HQ, JSpOC, and STRAT to determine whether JSpOC can send NASA's template to China**
  - STRAT agreed with OSD (P) that JSpOC can't send our template
  - It is unlikely that NASA will be allowed by Congress to make this exception in communication
  - Next step is to approach State and see if they are willing
  - HQ SMD/Justin Tilman re-reviewing FSO template in light of recent China developments to see if wording should be changed
  - JSpOC agreed to approve the ODR with caveats so that we have redistribution permission to use the template (not yet received)
- **Mar 2015: JSpOC reports that scripts have been developed and implemented that coordinate reporting between Goddard OSAs and CA Shop OSAs to ensure that FSOs don't receive two conflicting reports**

FSO Template Status: Template Sample (1 of 2)

Theoretical Example—fictitious date

To the operator of Envisat:

NASA has identified a close approach between the satellite Aura (satellite catalog number 28376) and the satellite Envisat (satellite catalog number 27386). The Time of Closest Approach (TCA) is 2014 Jan 23 12:34:56 UTC. The miss distance prediction as of 2014 Jan 17 18:00:00 UTC is 45.0 meters and the NASA Robotic Conjunction Assessment Risk Analysis (CARA) team is computing a Collision Probability of 1.42E-2, assuming a combined hard-body radius of 20 m.

We believe this close approach poses a high collision risk if neither satellite maneuvers. The owner-operator of Aura plans to maneuver its satellite between now and the time of closest approach. This maneuver is expected to mitigate the risk of collision. Is it possible to avoid maneuvering your satellite before the time of closest approach? If not and you are planning to execute a maneuver between now and time of closest approach, would it be possible to share your plans with the CARA Team in an effort to avoid a collision? If so, please share your plans in the form of (a) an ephemeris modeling the maneuver, or (b) pre- and post-maneuver state vectors.

Aura is currently planning a 5.2 cm/s orbit raise maneuver on 2014 Jan 20, at 18:00:00 UTC. We expect to provide status updates daily at approximately 15:00 UTC.

As of 2014 Jan 17 19:00:00 UTC, the current MJ2000 Predicted Post-Maneuver State Vector of Aura is

Epoch: 2014 Jan 20 18:15:00.000 UTC
<X, Y, Z; VX, VY, VZ> (km; km/s): <1234.000, 2345.000, 3456.000; 4.000000, 5.000000, 6.000000>

FSO Template Status: Template Sample (2 of 2)

Theoretical Example—fictitious date

NASA prefers that both spacecraft not maneuver to mitigate the risk of the same close approach, in order to prevent adding uncertainty to the problem. From a safety perspective, NASA prefers that any maneuver by one of the involved spacecraft not occur within 24 hours of a maneuver by the other involved spacecraft.

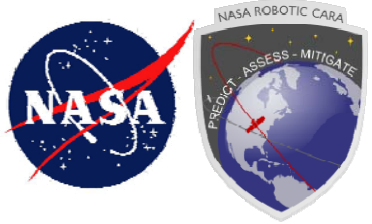
If your organization has established an account on Space-Track.org, the JSpOC may be able to provide you with Conjunction Summary Messages (CSMs) to assist in your risk assessment.

NOTE: You may receive an automated message from the US Joint Space Operations Center (JSpOC) containing information similar to what is presented here. The information contained in such an automated message may differ from the data presented here, although the data presented here do originate from the JSpOC as well.

If you have any questions, please contact the NASA Robotic Conjunction Assessment Risk Analysis (CARA) team via email at cara-ops@lists.nasa.gov; via the CARA Operations Center phone at +1-301-286-9545 from 0800-1600 US Eastern Time, Monday through Friday; or via the CARA on-call cell phone at +1-301-789-4306 outside of those hours.

FSO Template Status: Progress To Date

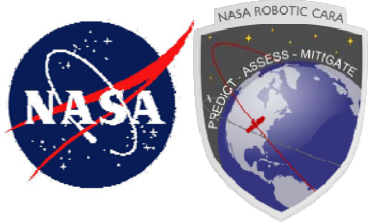
#	Activity	Responsible Party	Status
✓	Draft template and instructions	CARA / ESMO	Complete.
✓	Review template	MOWG	Complete.
✓	Approve template	NASA HQ	Complete.
4.	Approval to redistribute JSpOC data for qualified events	USSTRATCOM	In review.
5.	Procedure to contact FSO using template	US DoS	In review.



UPCOMING SOFTWARE RELEASES

CAS 8.2

- **Planned enhancements – Summary Report**
  - Hyperlinks from Summary to Details sections
  - Satellite-specific mission threshold
  - O/O RIC + uncertainty time history
  - ASW and O/O conjunction plane plots
  - Event flags
  - Pc in Vegas Odds
  - Current (screened) ephemeris end date
- **Planned enhancements – other**
  - Performance improvements (30-60 minutes)
  - Text message alerts
- **Target delivery of September 2015**

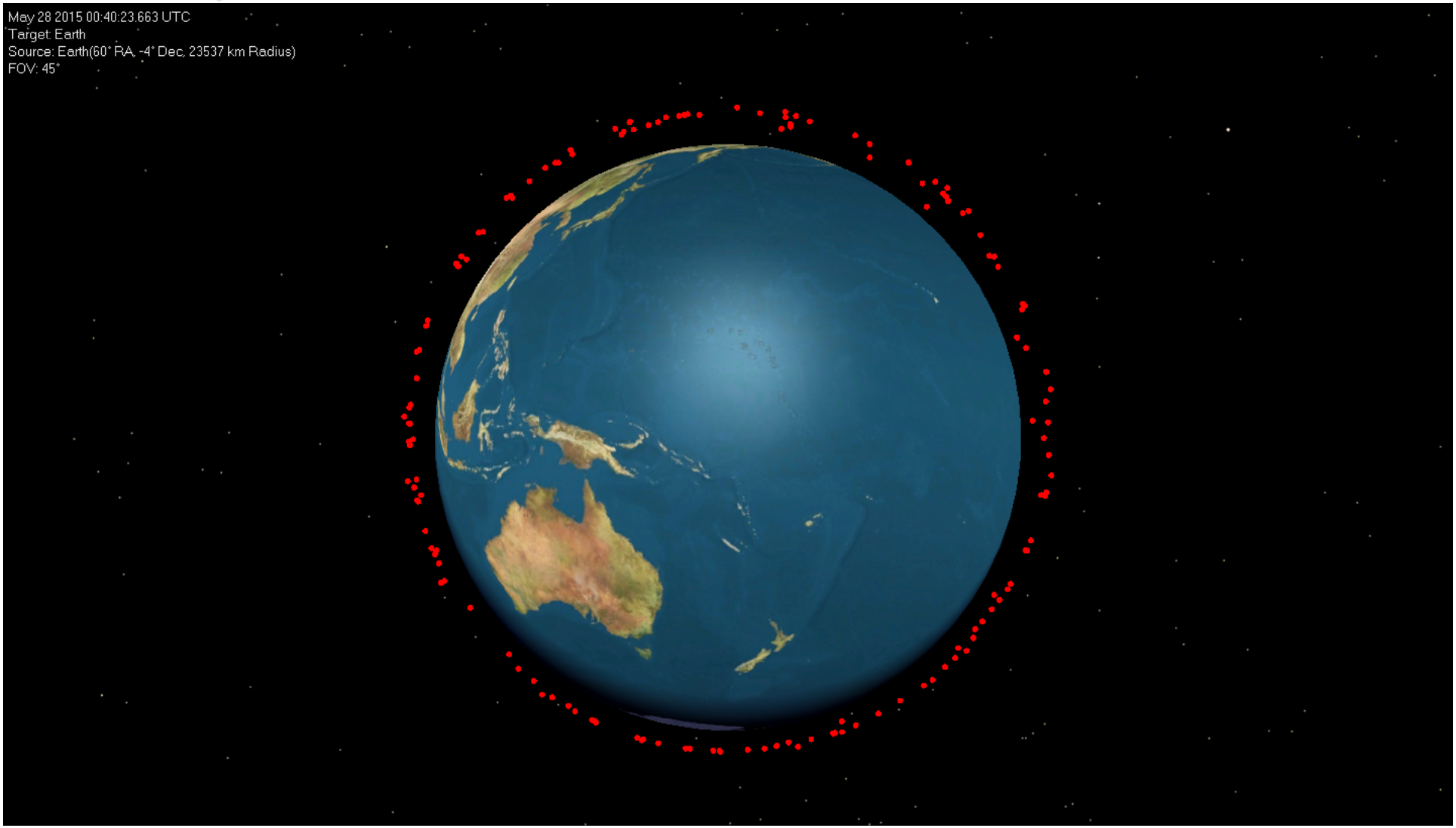


SPECIAL TOPICS

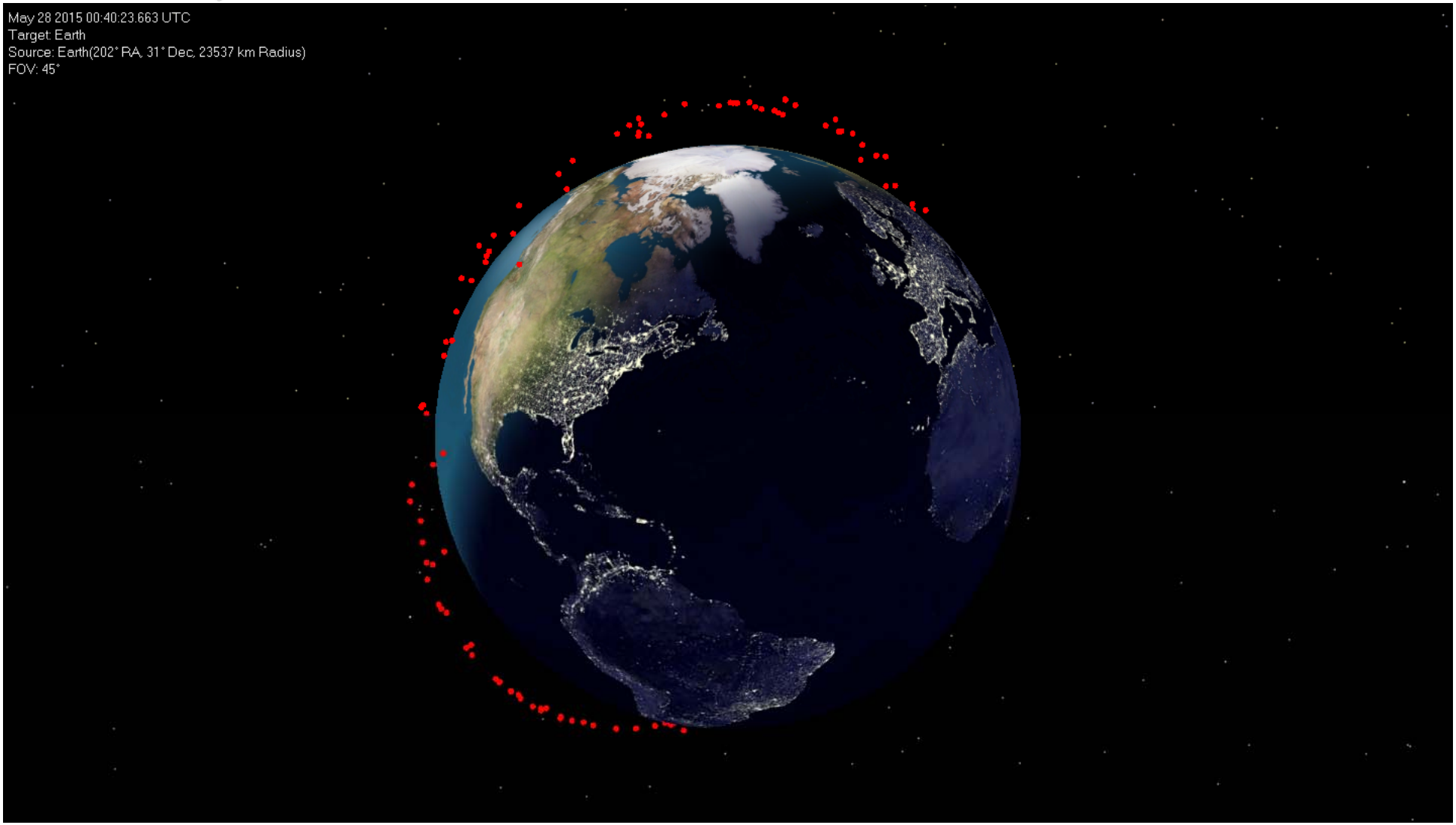
DMSP F13 Breakup Status

- **On 3 FEB 2015, CARA was notified of a potential break-up of the DMSP FD-2 F13 satellite**
- **Suspected cause of the break-up: on-board battery explosion**
- **149 pieces catalogued, of which 2 have re-entered**
  - Any trackable pieces without permanent catalog IDs exist as “AnalystSats” and are screened against though the CARA process
- **To date, CARA has observed hundreds of monitor volume conjunctions with catalogued DMSP F-13 debris**
  - Most with other DMSP satellites
  - Some have been with A-Train satellites, but none have been high risk

DMSP F13 Breakup Status



DMSP F13 Breakup Status

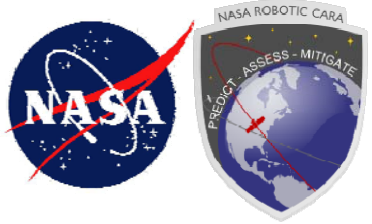


“Surprise” / “Late Notice” Events

- **“Late-Notice” HIEs are a legitimate concern of O/Os**
  - Close to TCA, a high-Pc conjunction appears “out of nowhere”
  - Close to TCA, a low-Pc conjunction suddenly becomes an HIE
  - Either less than desirable from an operational and planning perspective (CARA and O/O)
- **Need to understand such events in more depth**
  - Determine “expected” miss sigma level changes for LEO events
  - Develop (from data mining) clear definition of “late-breaking” HIE
    - Also partially defined by O/O maneuver timelines
  - Establish different categories of late-notice HIEs and link to root causes
  - Compute likelihood for a late-notice HIE in any given situation
  - Ensure JSpOC screening and CARA risk assessment processes are minimizing this likelihood to the extent possible
  - Examine some specific case studies
- **Study effort begun; Users Forum on topic planned for this summer**
- **MOWG Action item 1410-01**

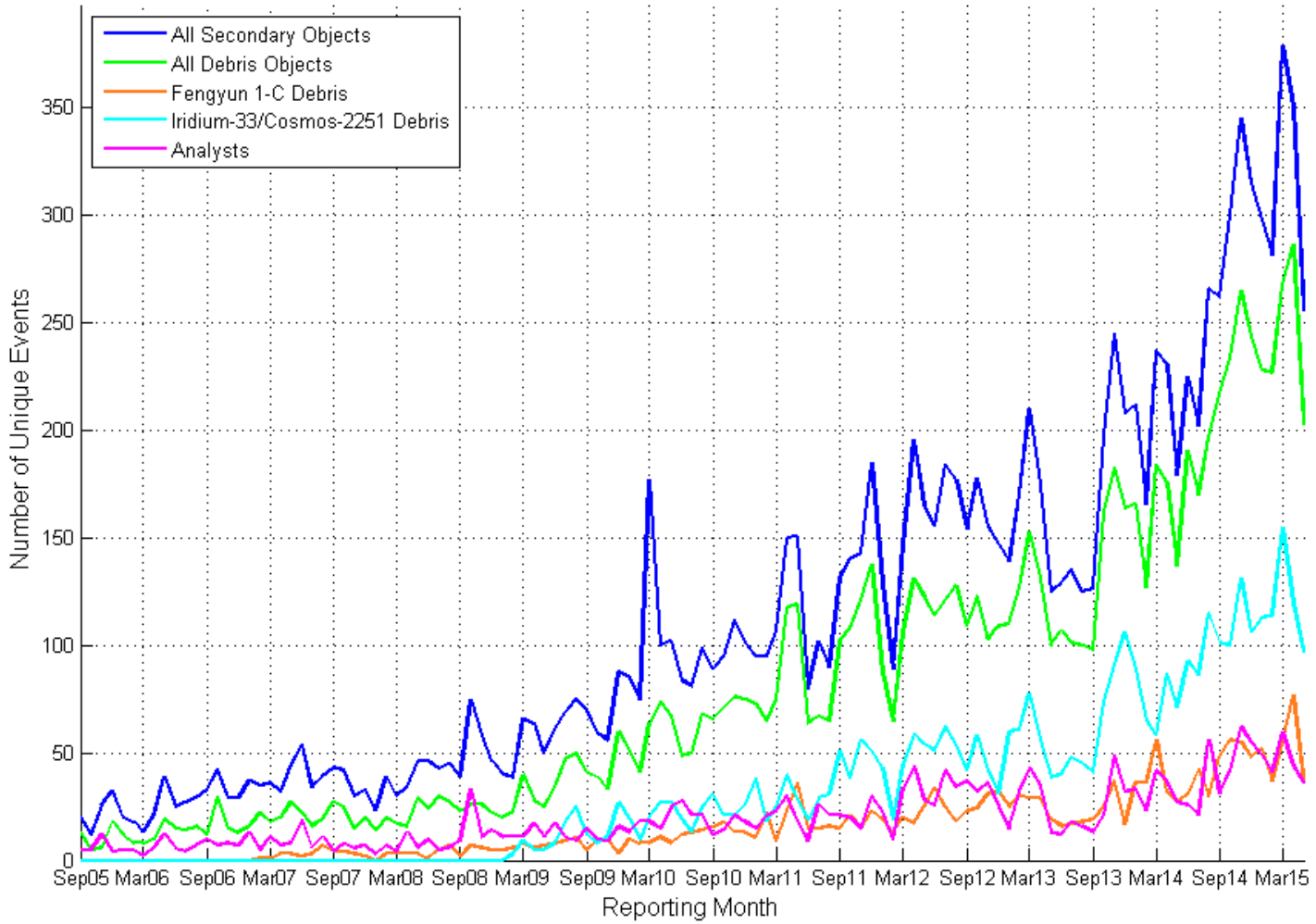
Ephemeris Naming Convention

- **CARA currently processes a maximum of 1 O/O ephem per mission per report delivery**
- **Sometimes missions deliver multiple ephems**
  - Burn and no-burn case
  - Multiple RMM options
- **To improve clarity, we are working towards a new naming convention, to add the following strings to the file name**
  - "_NOMINAL" – contains the nominal plan (i.e. trajectory you intend to follow), whether that includes burns or not
  - "_NOBURN" – contains no burns (not necessary to deliver if _NOMINAL contains no burns)
  - "_SPMANV" – any ephem that contains burns but is not the _NOMINAL
- **OCO-2 and other non-constellation missions are using this convention already**
- **Using this convention will mitigate the risk of having the wrong ephemeris screened**
  - Plan to have this capability in place by mid-July

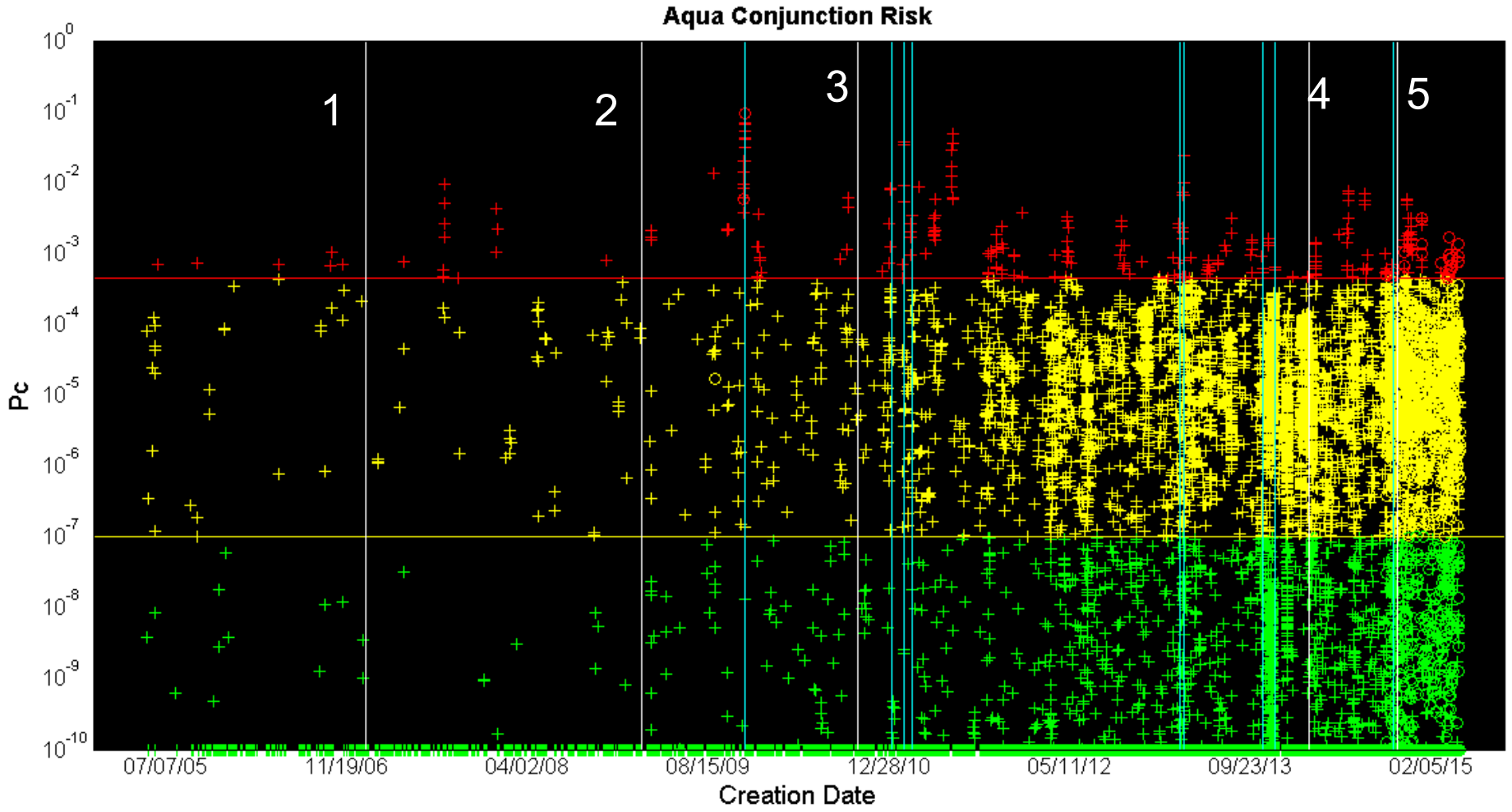


CARA STATISTICS

Number of Conjunctions with Current ESC Missions



Aqua Historical Events by Risk Category



Major Events

1. Fengyun 1-C debris, 11 JAN 2007
2. Iridium-Cosmos debris, 12 FEB 2009
3. First screening volume update ca. Fall 2010
4. Second LEO screening, 1 MAR 2014
5. CONOPS, 1 NOV 2014

CA Users Forum

- **NASA Robotic CARA Team hosts Users Forums to:**
  - Communicate upcoming changes in CA process
  - Present analysis results
  - Debrief high interest events & discuss lessons learned
  - Address CA 'Hot Topics'
  - Conduct open forum with CA users: present & future
  - Solicit comments/ideas/input from user community
- **6 Users Forums in past 12 months**
  - July 2014: Space Weather Trade Space and Synthesized Covariance
  - August 2014: Updates to CARA CONOPS
  - December 2014: Legacy Report Closeout
  - February 2015: Upcoming Software Release Enhancements
  - March 2015: Maneuver Trade Space 2.0
  - April 2015: Owner/Operator Predicted Covariance Recommendations

High Interest Events

- **From 1 Oct. 2015 – 1 Jun. 2015:**
  - Supported 17 High Interest Events (HIEs) for constellation missions resulting in:
    - RMM (10), or
    - Re-plan/ postpone/cancel a nominal maneuver (7)
  - Supported 175 ESC events where "work tier" ≥ 1
    - Metric for level of CARA support
      - Dependent on:
        - » Risk
        - » Necessary level of O/O support
      - Levels and breakdown on next slide

Tactical Work Tiers

- **The four tiers are defined as:**
  - Tier 1: Notify O/O (email/phone call)
    - **92** events for constellation missions, Oct. 1 – Jun. 1
    - Sometimes to communicate low risk despite appearance
  - Tier 2: Brief O/O (slide package/Maneuver Trade Space plots)
    - **37** events
    - Generally not as common since most members maneuverable
  - Tier 3: Plan mitigation action
    - **29** events
    - Maneuver waived; conservative course of action taken
  - Tier 4: Execute mitigation action/waive/replan maneuver
    - **17** events
    - One RMM or waive/replan of nominal maneuver every ~15 days, on average
  - Total Work Tier events: 175
    - ~6 events per week, on average
- **These totals are just for 10 of our ~65 missions**
  - Total CARA work tiers since October: 309 (of which 175 are ESC)
  - Total CARA work tier 3 & 4 since October: 59 (of which 46 are ESC)

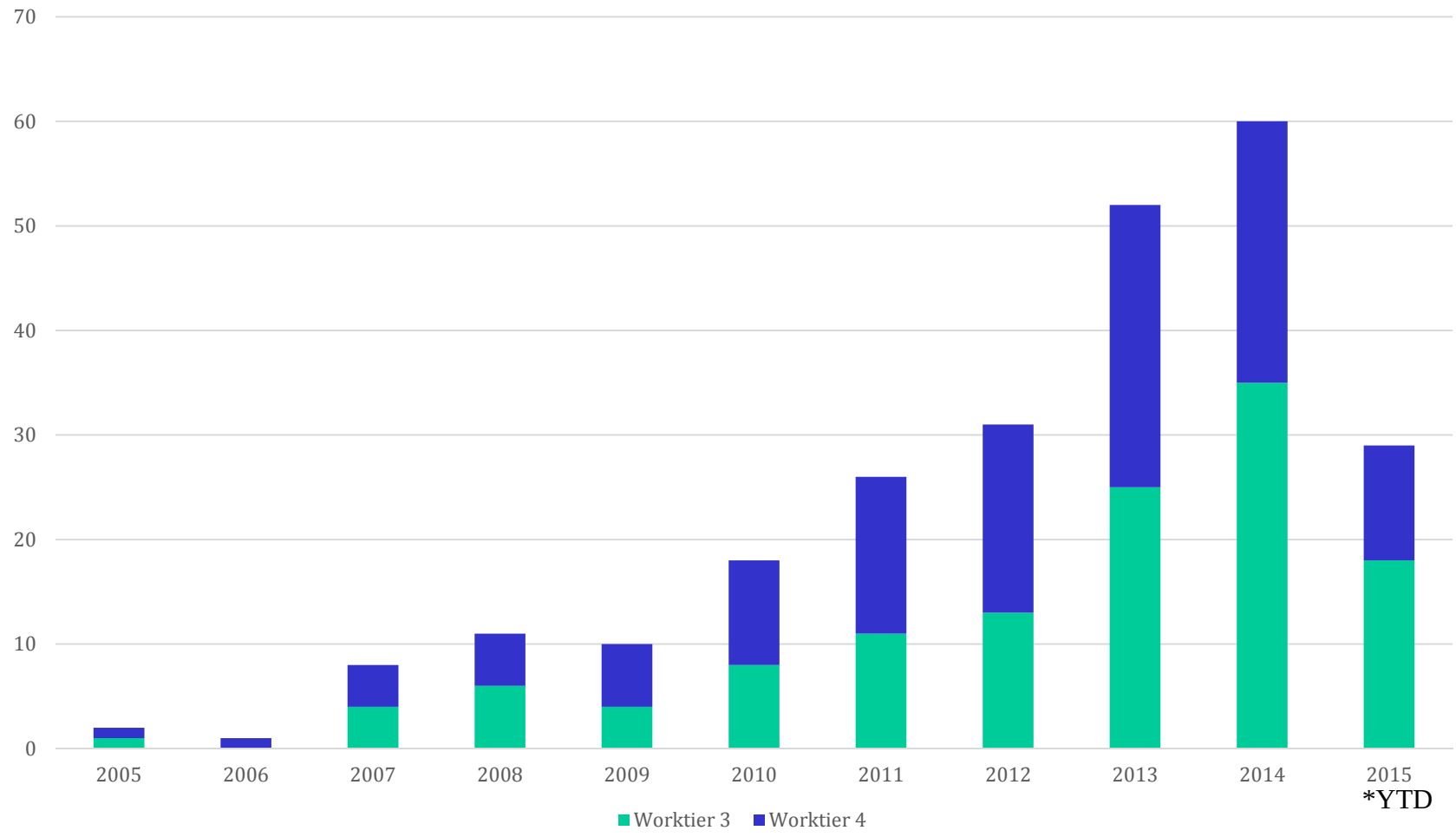
Cumulative Work Tier Stats (as of 1 Oct 2014)

Historical	Work Tier 1	Work Tier 2	Work Tier 3	Work Tier 4	Total
Landsat 5	31	3	4	5	43
Landsat 7	52	15	7	13	87
Terra	80	13	20	15	128
EO-1	43	6	4	2	55
SAC-C	33	3	2	1	39
Aqua	78	23	26	20	147
ICESat	3	4	0	0	7
SORCE	3	0	0	0	3
Aura	98	21	28	15	162
Parasol	58	6	6	4	74
CloudSat	63	4	9	16	92
CALIPSO	115	3	3	7	128
GCOM-W1	20	6	4	12	42
Landsat 8	77	4	5	8	94
OCO-2	11	3	1	3	18
Total	765	114	119	121	1119

*Note that Tier 1 statistics are incomplete for Jan. 2005 – Aug. 2010. They were compiled using all past records on file and do not account for all events monitored during said time period.

2015	Work Tier 1	Work Tier 2	Work Tier 3	Work Tier 4	Total
Landsat 7	2	3	1	0	6
Terra	9	4	4	2	19
EO-1	2	1	1	0	4
Aqua	3	3	4	1	11
Aura	10	2	3	3	18
CloudSat	4	1	1	1	7
CALIPSO	9	0	0	0	9
GCOM-W1	3	2	1	2	8
Landsat 8	7	2	1	1	11
OCO-2	6	2	1	1	10
Total	55	20	17	11	103

HIE History for 705-km Constellations (as of 1 Jun. 2015)



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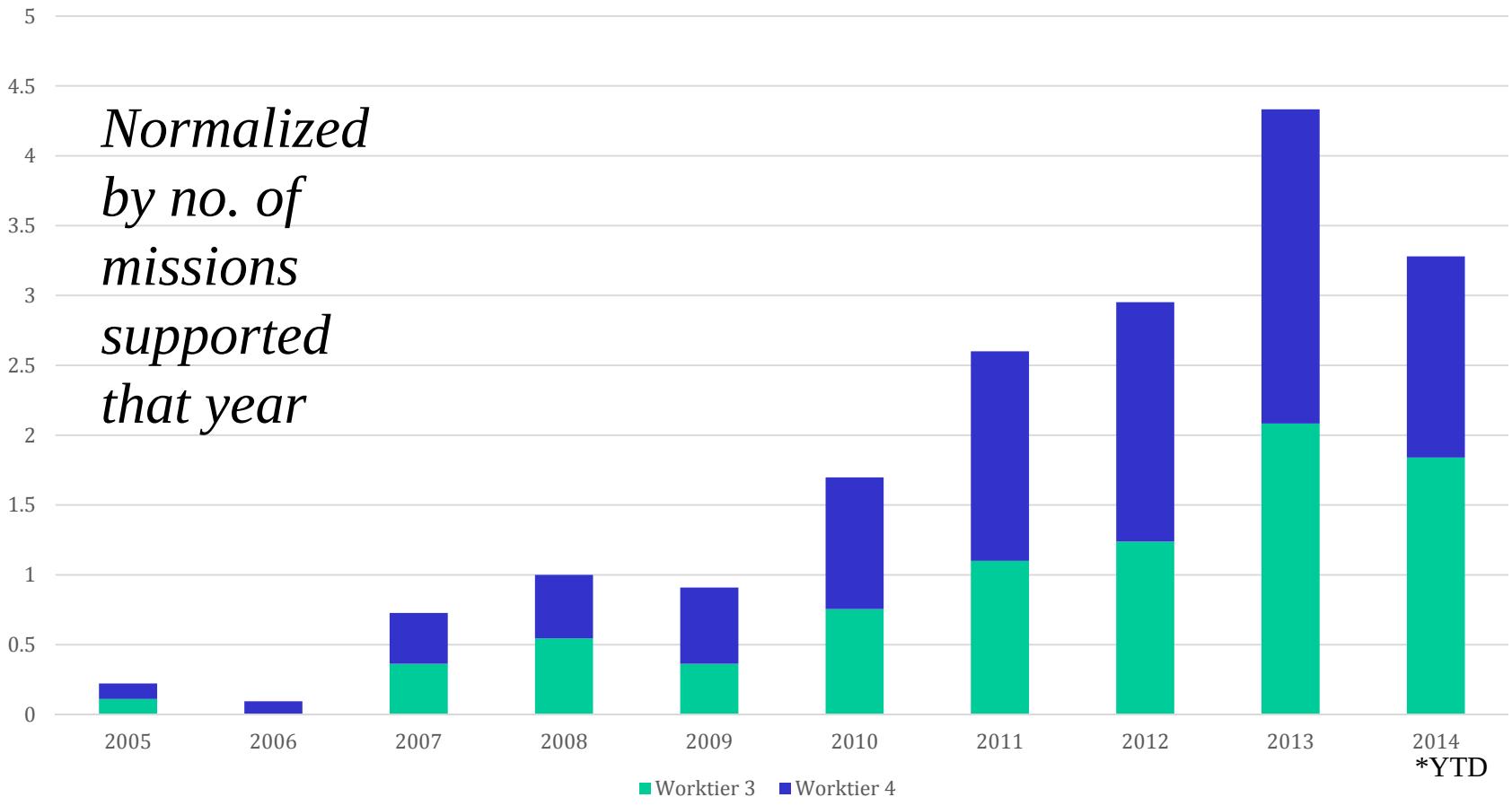


New Risk Mitigation Maneuvers for 705-km Constellations

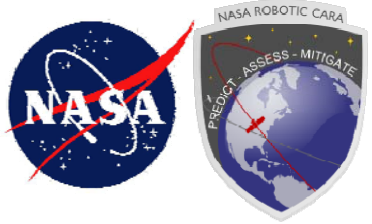
Primary Object	Secondary Object	Maneuver Date	TCA (GMT)	Minimum Miss Distance Observed [m]	Maximum Pc Observed
GCOM-W1	SL-16 Debris	12 Oct 2014	13 Oct 2014 08:03	1900	6.75E-04
Aqua	Unknown	21 Oct 2014	21 Oct 2014 04:17	4935	6.90E-04
GCOM-W1	Cosmos 1275 Debris	09 Nov 2014	09 Nov 2014 23:44	69	3.91E-03
Terra	Iridium 33 Debris	31 Dec 2014	01 Jan 2015 06:24	206	9.67E-04
OCO-2	Cosmos 2251 Debris	01 Jan 2015	02 Jan 2015 07:58	152	6.70E-04
CloudSat	SL-8 Debris	14 Mar 2015	15 Mar 2015 20:07	40	3.72E-04
Landsat 8	Cosmos 2251 Debris	10 Apr 2015	10 Apr 2015 14:37	46	8.68E-04
GCOM-W1	DMSP 5D-2 F11 Debris	13 Apr 2015	13 Apr 2015 06:06	1439	1.46E-03
GCOM-W1	SJ-11-01	20 May 2015	22 May 2015 14:27	455	2.27E-03
Terra	Cosmos 2251 Debris	27 May 2015	27 May 2015 23:13	57	1.86E-02

Re-planned, Postponed, Waived Off Maneuvers (705-km Constellations) cont.

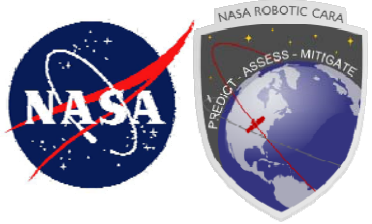
Primary Object	Secondary Object	Maneuver Date	TCA (GMT)	Minimum Miss Distance Observed O/O [m]	Minimum Miss Distance Observed ASW [m]	Maximum ASW Pc Observed
Terra	Cosmos 2251 Debris	13 Nov 2014	08 Nov 2014 22:46	133	6067	0.00E+00
Calipso	CZ-2C Debris	05 Dec 2014	06 Dec 2014 06:49	1409	N/A	N/A
Terra	Iridium 33 Debris	12 Dec 2014	13 Dec 2014 15:44	4110	4320	2.13E-04
Aura	Fengyun 1-C debris	28 Jan 2015	24 Jan 2015 13:34	1292	1460	6.82E-04
Aura	CZ-2C Debris	28 Feb 2015	07 Feb 2015 02:16	298	153	1.04E-03
Aura	CBERS 1 Debris	28 Feb 2015	18 Feb 2015 22:36	150	607	6.06E-09
Aqua	Cosmos 2251 Debris	22 May 2015	22 May 2015 23:47	149	395	1.24E-04

CARA Open House

- **CARA is planning a first-ever Open House**
  - All CARA Users invited
- **Date set for 29-30 September 2015**
- **Planned Events**
  - Overview of CARA Activities and Plans
  - Selected technical briefings (Users Forums)
  - Individual mission demo/tours
  - CARA training short-course
  - Networking



OPEN DISCUSSION



BACKUP

Risk Mitigation Maneuvers for 705-km Constellations

Primary Object	Secondary Object	Maneuver Date	TCA (GMT)	Minimum Miss Distance Observed [m]	Maximum Pc Observed	Maximum F-value Observed
Terra	SCOUT G-1	10/21/2005	10/23/2005 20:53	37	8.20E-02	9.97
PARASOL	AnalystSat	1/16/2007	1/17/2007 8:43	43	1.80E-02	8.91
Terra	FengYun 1-C Debris	6/22/2007	6/23/2007 21:44	18	1.60E-01	8.73
CloudSat	SINAH 1	7/4/2007	7/6/2007 6:51	38	4.70E-02	9.22
Aura	TRIAD 1 Debris	6/26/2008	6/27/2008 15:34	11	4.80E-01	9.62
CloudSat	Delta I Debris	7/20/2008	7/21/2008 4:38	90	2.90E-03	8.48
PARASOL	Fengyun 1-C Debris	10/19/2008	10/20/2008 10:59	82	2.10E-02	6.42
CloudSat	Cosmos 2251	4/23/2009	4/24/2009 13:29	52	4.80E-02	9.82
EO-1	SL-16 Debris	5/11/2009	5/12/2009 16:59	43	1.60E-02	8.11
PARASOL	Fengyun 1-C Debris	9/29/2009	9/30/2009 10:54	9	1.20E-01	8.81
Aqua	Fengyun 1-C Debris	11/25/2009	11/26/2009 15:36	25	7.00E-02	9.23

Risk Mitigation Maneuvers for 705-km Constellations cont.

Primary Object	Secondary Object	Maneuver Date	TCA (GMT)	Minimum Miss Distance Observed [m]	Maximum Pc Observed	Maximum F-value Observed
Landsat-7	FORMOSAT 3D	12/11/2009	12/16/2009 18:54	92	2.30E-02	9.07
Terra	Iridium 33 Debris	1/22/2010	1/23/2010 20:46	244	5.70E-03	8.15
Landsat-5	AnalystSat	4/1/2010	4/1/2010 20:49	68	5.50E-03	7.6
CloudSat	AnalystSat	8/17/10 & 8/18/10	8/18/2010 5:25	34.9	1.17E-02	7.1
Landsat-5	Cosmos 2251 Debris	8/24/2010	8/27/2010 12:58	55.8	5.15E-03	7.6
CloudSat	SL-16 Debris	10/11/2010	10/12/2010 4:15	230	3.80E-03	8.9
CloudSat	Cosmos 2251 Debris	10/13/2010	10/13/2010 23:58	1560	4.25E-03	6.2
Aura	Cosmos 2251 Debris	11/22/2010	11/24/2010 11:16	50	3.90E-02	9.5
Aqua	Cosmos 2251 Debris	1/2/2011	1/5/2011 18:17	94	8.40E-03	6.4
Aqua	Iridium 33 Debris	2/8/2011	2/8/2011 19:32	41	4.70E-02	8.6
CALIPSO	OV2-1	2/18/2011	2/19/2011 20:47	95	2.20E-04	9
Aqua	Thorad Agena D Debris	3/1/2011	3/2/2011 2:45	204	3.41E-03	9

Risk Mitigation Maneuvers for 705-km Constellations cont.

Primary Object	Secondary Object	Maneuver Date	TCA (GMT)	Minimum Miss Distance Observed [m]	Maximum Pc Observed	Maximum F-value Observed
CloudSat	Aqua	6/18/2011	7/1/2011 0:13	280	UNK	N/A
CloudSat	Terra	10/6/2011	11/7/2011 0:33	1125	UNK	UNK
Landsat-7	Cosmos 374 Debris	11/29/2011	11/30/2011 18:07	92	4.75E-03	7
CloudSat	FengYun 1-C Debris	12/14/2011	12/15/2011 18:59	220	1.79E-02	UNK
Landsat-7	FengYun 1-C Debris	3/8/2012	3/9/2012 19:32	498	2.02E-03	9.1
Landsat-7	Meteor 1-10 Debris	4/17/2012	4/18/2012 8:14	32	3.73E-02	7.8
Aura	Cosmos 2251 Debris	5/16/2012	5/17/2012 19:09	81	4.70E-04	8
Landsat-5	Thorad Agena D Debris	6/29/2012	7/1/2012 1:46	34	5.42E-03	9
CloudSat	SINAH 1	9/7/2012	9/8/2012 4:57	61	3.55E-03	9.2
GCOM-W1	Fengyun 1C Debris	9/8/2012	9/8/2012 21:18	241	1.59E-03	7.3

Risk Mitigation Maneuvers for 705-km Constellations cont.

Primary Object	Secondary Object	Maneuver Date	TCA (GMT)	Minimum Miss Distance Observed [m]	Maximum Pc Observed	Maximum F-value Observed
GCOM-W1	SL-16 Debris	9/25/2012	9/25/2012 20:54	125	4.68E-03	8.4
CALIPSO	Cosmos 2251 Debris	10/2/2012	10/2/2012 22:28	5	5.90E-02	9.6
PARASOL	SL-16 Debris	11/25/2012	11/25/2012 18:45	78	8.32E-03	8.6
CALIPSO	Cosmos 2251 Debris	1/5/2013	1/6/2013 13:51	94	2.43E-03	8.7
Landsat-5	AnalystSat	2/12/2013	2/13/2013 12:29	58	5.86E-03	7.5
Aqua	Thor Ablestar Debris	3/10/2013	3/12/2013 4:02	74	2.57E-03	8.5
CALIPSO	Iridium 33 Debris	3/20/2013	3/20/2013 22:23	129	5.72E-03	9.3
Aqua	Iridium 33 Debris	3/23/2013	3/23/2013 11:17	329	3.92E-04	6.4
Terra	Cosmos 1174 Debris	3/24/2013	3/26/2013 4:24	113	2.38E-03	9.3
CloudSat	Fengyun 1C Debris	4/25/2013	4/26/2013 11:39	529	1.37e-03	6.8
LDCM	NOAA 13 Debris	5/5/2013	5/6/2013 19:53	248	1.96E-02	9.6
Landsat-7	CZ-4 Debris	5/9/2013	5/10/2013 14:21	128	5.14E-04	8.9

Risk Mitigation Maneuvers for 705-km Constellations cont.

Primary Object	Secondary Object	Maneuver Date	TCA (GMT)	Minimum Miss Distance Observed [m]	Maximum Pc Observed	Maximum F-value Observed
GCOM-W1	CZ-4 Debris	10 May 2013	11 May 2013 22:24	69	6.81E-03	7.4
GCOM-W1	Fengyun 1C Debris	23 Jun 2013	25 Jun 2013 13:00	162	5.58E-03	9.4
Landsat 8	AnalystSat	15 Aug 2013	16 Aug 2013 11:39	1250	1.28E-03	6.4
Terra	CZ-4 Debris	18 Aug 2013	19 Aug 2013 07:43	79	6.72E-02	9.3
Aura	SJ-11-02	02 Sep 2013	03 Sep 2013 07:02	320	2.23E-04	8.5
GCOM-W1	Fengyun 1C Debris	19 Sep 2013	20 Sep 2013 05:55	184	1.69E-03	7.2
CALIPSO	Cosmos 397 Debris	24 Sep 2013	24 Sep 2013 18:31	115	2.42E-03	8.3
Landsat 7	SL-8 Debris	01 Oct 2013	02 Oct 2013 20:53	58	7.51E-04	8.7
Aqua	Iridium 33 Debris	25 Oct 2013	25 Oct 2013 04:27	689	8.99E-04	8.8
Terra	Fengyun 1C Debris	17 Nov 2013	18 Nov 2013 05:42	272	1.01E-02	8.5

Risk Mitigation Maneuvers for 705-km Constellations cont.

Primary Object	Secondary Object	Maneuver Date	TCA (GMT)	Minimum Miss Distance Observed [m]	Maximum Pc Observed	Maximum F-value Observed
Aqua	Cosmos 2251 Debris	28 Nov 2013	28 Nov 2013 22:28	373	6.41E-04	8.1
Terra	CZ-4 Debris	10 Feb 2014	10 Feb 2014 11:52	152	1.24E-02	8.5
Terra	Delta 1 Debris	2014 Mar 21	23 Mar 2014 00:17	50	2.35E-03	8.6
Landsat 7	Delta 1 Debris	2014 Apr 15	16 Apr 2014 17:10	362	8.63E-03	9.1
GCOM-W1	Iridium 33 Debris	2014 Apr 22	22 Apr 2014 17:11	223	3.39E-03	8.0
Landsat 7	Cosmos 2251 Debris	27 May 2014	28 May 2014 06:19	127	2.31E-02	8.4
OCO-2	AnalystSat	24 Aug 2014	24 Aug 2014 01:47	147	8.84E-04	6.5
Landsat 8	Cosmost 2251 Debris	28 Aug 2014	30 Aug 2014 19:15	384	3.02E-03	9.1
Aura	Fengyun 1C Debris	29 Aug 2014	02 Sep 2014 12:32	408	1.19E-03	6.7
OCO-2	CZ-4B Debris	14 Sep 2014	14 Sep 2014 22:51	81	2.84E-04	7.8
Landsat 7	SL-8 Debris	25 Sep 2014	25 Sep 2014 22:47	1447	4.16E-04	7.1

Re-planned, Postponed, Waived Off Maneuvers (705-km Constellations)

Primary Object	Secondary Object	Maneuver Date	TCA (GMT)	Minimum Miss Distance Observed O/O [m]	Minimum Miss Distance Observed ASW [m]	Maximum Pc Observed
Terra	Titan 3C Transtage Debris	UNK	1/12/2006 17:46	88	334	0.00E+00
Aura	Titan 3C Transtage Debris	6/17/2008	6/13/2008 3:26	618	5671	N/A
Aura	DMSP 5D-2 F11 debris	6/17/2008	6/15/2008 20:34	628	7340	N/A
Landsat-7	Fengyun 1-C debris	2/3/2009	1/14/2009 9:49	380	1055	5.13E-05
CALIPSO	CZ-4 Debris	11/23/2010	11/23/2010 3:12	1735	421	1.60E-03
CloudSat	Monitor-E/SL-19	11/23/2010	11/23/2010 13:47	150	1377	0.00E+00
Landsat-7	AnalystSat	12/21/2010	12/21/2010 19:43	673	441	2.35E-03
Aqua	CloudSat	6/8/2011	5/22/2011 0:00	UNK	UNK	UNK
Aqua	Fengyun 1-C debris	6/23/2011	6/23/2011 17:27	370	66	4.92E-02
Aqua	COSMOS 2251 Debris	8/25/2011	8/29/2011 3:57	195	30739	0.00E+00
Aura	COSMOS 2251 Debris	9/8/2011	9/3/2011 5:57	40	50	2.20E-03
Landsat-7	CZ-2C Debris	10/6/2011	10/9/2011 1:16	87	3860	1.68E-06

Re-planned, Postponed, Waived Off Maneuvers (705-km Constellations) cont.

Primary Object	Secondary Object	Maneuver Date	TCA (GMT)	Minimum Miss Distance Observed O/O [m]	Minimum Miss Distance Observed ASW [m]	Maximum Pc Observed
Aqua	CZ-4 Debris	10/25/2011	10/26/2011 11:13	12	1349	1.80E-03
Aqua	Titan 3C Transtage Debris	12/20/2011	12/16/2011 19:36	388	45775	0.00E+00
Terra	Nigeriasat-2	5/31/2012	6/1/2012 22:49	190	19970	0.00E+00
Landsat-7	Fengyun 1-C Debris	6/19/2012	6/21/2012 13:40	415	641	1.01E-04
GCOM-W1	Iridium 33 Debris	6/28/2012	6/29/2012 6:23	3487	4397	N/A
Aura	AnalystSat	8/29/2012	9/2/2012 13:28	230	63	2.74E-03
Landsat-5	COSMOS 2251 Debris	9/13/2012	9/11/2012 17:47	103	97	4.83E-03
Aqua	AnalystSat	9/13/2012	9/16/2012 18:50	63005	345	0.00E+00
Aqua	COSMOS 2251 Debris	1/25/2013	1/28/2013 19:46	235	190	3.23E-04
Aura	Latinsat B	4/3/2013	3/24/2013 22:04	793	5096	7.28E-16
Aura	SL-16 Debris	4/3/2013	3/30/2013 3:08	80	20095	3.24E-103
LDCM	Atlas Centaur R/B	4/3/2013	4/4/2013 4:11	227	5707	1.88E-52

Re-planned, Postponed, Waived Off Maneuvers (705-km Constellations) cont.

Primary Object	Secondary Object	Maneuver Date	TCA (GMT)	Minimum Miss Distance Observed O/O [m]	Minimum Miss Distance Observed ASW [m]	Maximum Pc Observed
Aqua	PSLV Debris	30 Apr 2013	24 Apr 2013 07:44	238	3810	6.63E-08
Landsat 8	SL-8 Debris	21 Jul 2013	23 Jul 2013 19:56	1549	266	1.26E-03
Landsat 8	NOAA 13 Debris	26 Sep 2013	28 Sep 2013 03:16	271	209	1.44E-08
Aura	Cosmos 2251 Debris	15 Nov 2013	18 Nov 2013 17:50	157	3822	1.27E-02
Aqua	SL-16 Debris	14 Jan 2014	09 Jan 2014 23:30	1402	3355	2.50E-05
Aqua	Cosmos 2251 Debris	14 Jan 2014	14 Jan 2014 17:24	7979	2930	4.06E-06
Terra	Magion 2	26 Feb 2014	26 Feb 2014 02:42	280	6806	1.14E-06
GCOM-W1	CZ-2D Debris	02 Apr 2014	27 Mar 2014 16:06	1454	11725	1.82E-04
CloudSat	AnalystSat	04 Apr 2014	03 Apr 2014 22:42	211	10269	1.30E-04
CloudSat	Thor Ablestar Debris	21 May 2014	22 May 2014 12:02	152	1199	9.00E-06
Aura	Cosmos 2251 Debris	19 Jun 2014	20 Jun 2014 05:22	137	64	8.80E-05
Landsat 8	Cosmos 2251 Debris	24 Sep 2014	24 Sep 2014 01:52	154	2628	0.00E+00

Normalizing HIE Trend Data

Year	No. of Missions	Notes
2005	9	L5, L7, Terra, Aqua, Aura, EO-1, Parasol, SAC-C, IceSAT
2006	10.5	Added Calipso and Parasol in April; 0.75 yrs each
2007	11	
2008	11	
2009	11	
2010	10.6	Stopped supporting IceSAT in August
2011	10	
2012	10.5	Added GCOM-W1 in May
2013	11	Added L8 in February; dropped Landsat 5 in June
2014	10.5	Added OCO-2 in July; dropped SAC-C, PARASOL
2015	10	