CNES International Conjunction Assessment Workshop

November 7-9, 2017

Earth Observing System (EOS) Aqua & Aura Space Weather Effects on Operational Collision Avoidance

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Cover Credit: NASA Solar Dynamics Observatory (SDO)

Topics

- **Conjunction Assessment & Operational Collision Avoidance**
- **Examples of Earth Science Constellation (ESC) Experience**
- **Conjunction Assessment Risk Analysis (CARA) Space Weather Research Efforts and Tools**
- **Case Study: Aura vs. 39858**
  - Case Study: Aura vs. 89477
- **Things that worked**
- **Questions**

What do we know about the effects of space weather modeling on conjunction assessment and collision avoidance?

Space Weather Events and Debris Avoidance Maneuver Planning

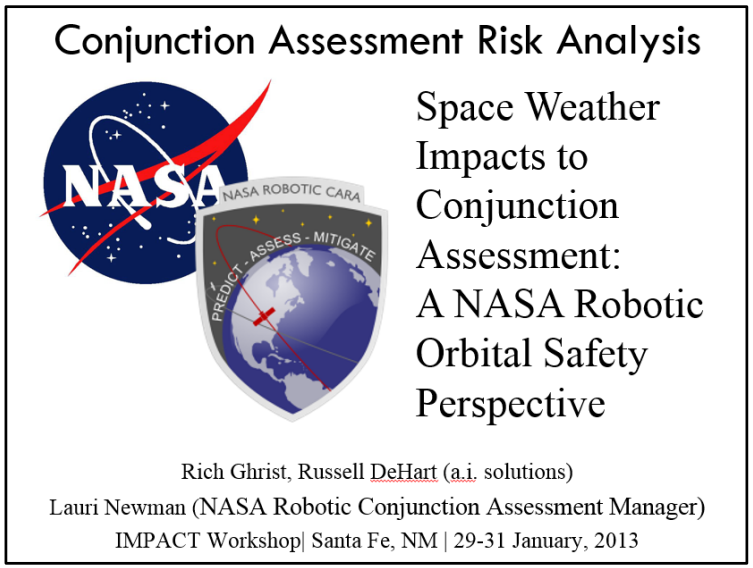
- **Joint Space Operations Center (JSpOC) space weather predictions based on:**
  - Jacchia-Bowman 2008 (JB08) and High Accuracy Satellite Drag Model (HASDM)
  - Anemomilos Solar Storm Prediction Model Disturbance Storm Time (Dst)
- **Typically Debris Avoidance Maneuver (DAM) planning begins ~24 to 72 hours prior to Time of Closest Approach (TCA) using the;**
  - Latest tracking data and latest predicted space weather and atmospheric density models
- **DAM planning is a joint effort by all parties of the Flight Support Team (FST)**
  - Flight Operations Team (FOT) and Flight Dynamics Team (FDT)
  - NASA Conjunction Assessment Risk Analysis (CARA) Team and
  - GSFC Orbital Safety Analyst (OSA)
- **Designed to allow sufficient time for the maneuver planning and screening process to ensure that the planned maneuver is safe to execute.**
- **Uncertainties due to space weather exist and complicate DAM planning:**
  - Arrival, confidence and magnitude of Solar Event affects predicted miss distances
  - Uncertainties on arrival time (typically plus or minus hours) and magnitude of Solar Events prior to TCA complicate evaluation in determining if a DAM is warranted or could possibly make matters worse

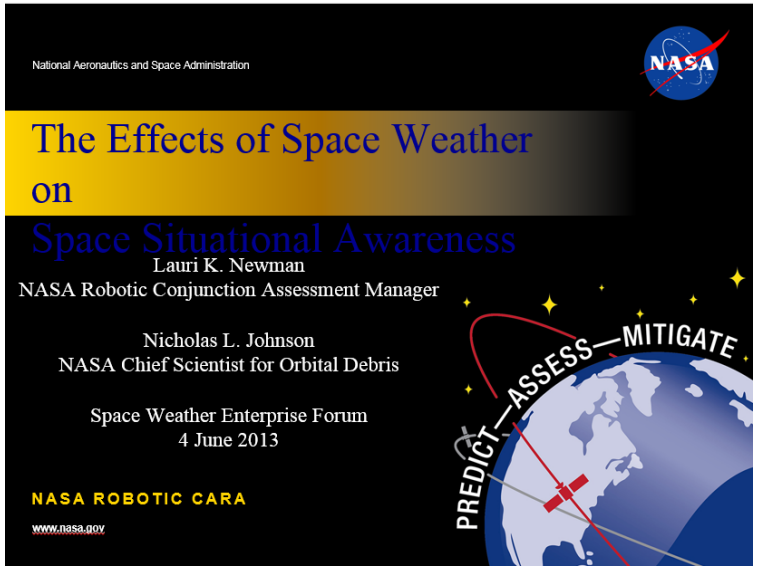
ESMO Experience with Space Weather

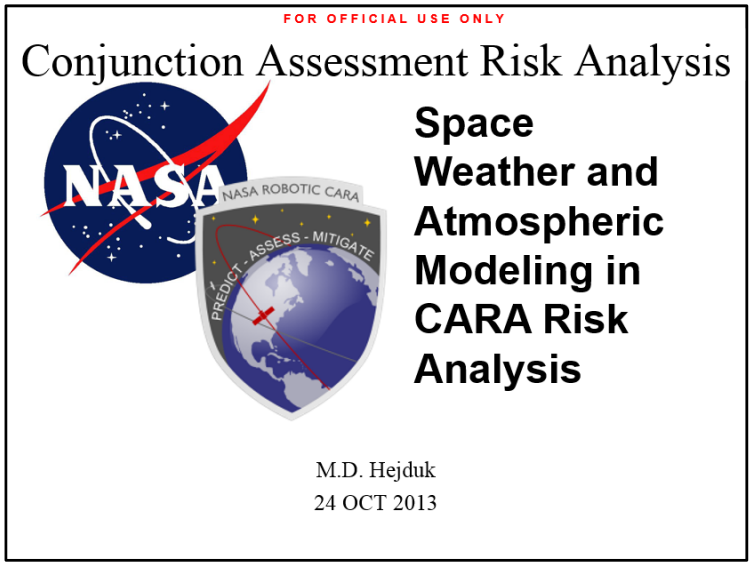
Examples from the International Earth Science Constellation (ESC)

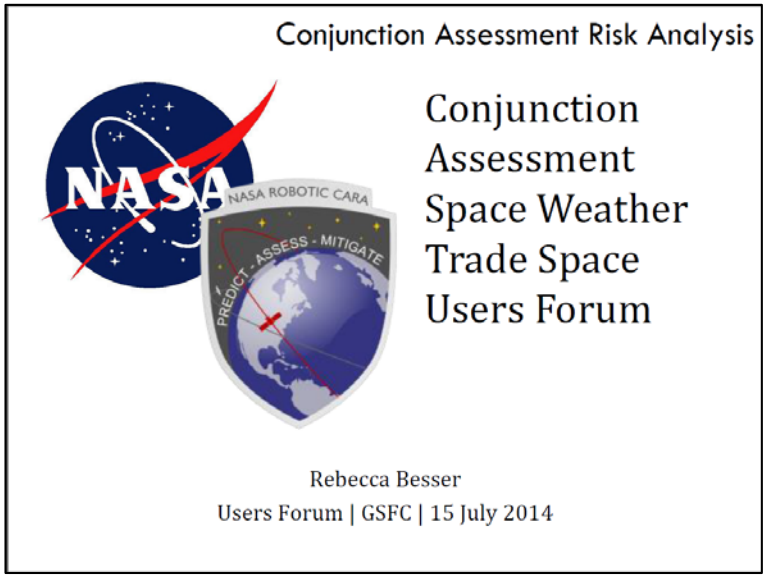
- **2011: CloudSat high interest event (HIE) with radial miss distance changing signs on successive updates (space weather?/modeling?)**
  - ESMO raised concerns about managing HIEs during solar activity
- **2014: 6th GSFC Space Weather Workshop (Aura/35380 TCA: 2014-02-16)**
  - CME predicted to arrive about 30-hours prior to planned potential DAM, Planned DAM waived off Saturday, February 12th
- **2015: 7th GSFC Space Weather Workshop (Aura/89477 TCA: 2015-08-29)**
  - Short-notice (16-hours), high-risk HIE complicated by intense solar and geomagnetic activity prior to planned DAM – Planned DAM waived off shortly before TCA
- **2016: ESC/A-Train Mission Operations Working Group (MOWG) Meeting Presentation: CARA Short-Notice HIEs – Matt Hejduk**
  - Aura vs. 89477: Concluded JSpOC space weather predictions missed significant solar storm was the most-likely cause of changes in Pc
- **2016: 8th GSFC Space Weather Workshop Presentation:**
  - CARA Conjunction Assessment Late-Notice HIEs (Hejduk & Pachura)
- **2017: 9th GSFC Space Weather Workshop (Aura/39858 TCA: 2017-09-10)**
  - High-risk HIE complicated by intense solar and geomagnetic activity

CARA Space Weather Presentations









CARA Space Weather Trade Space (SWTS) Tool

Flight Dynamics Support Services
FDSS-1021-0019
CODE 595

Space Weather Trade Space Tool

Issue Date: 21 JUL 2014

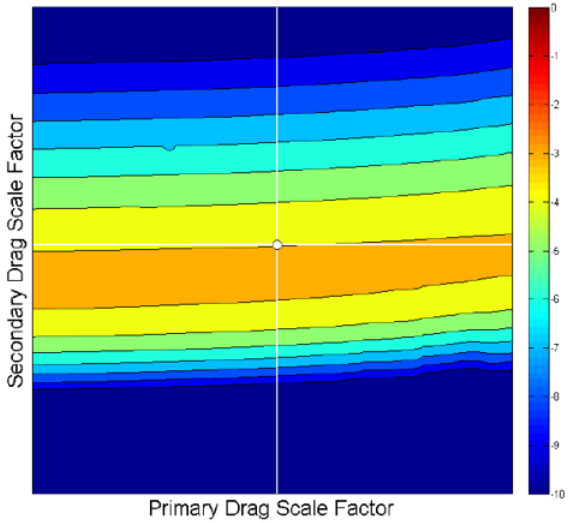
Prepared by:

Dr. Matt Hejduk
CARA Chief Engineer
a.i. solutions, Inc.

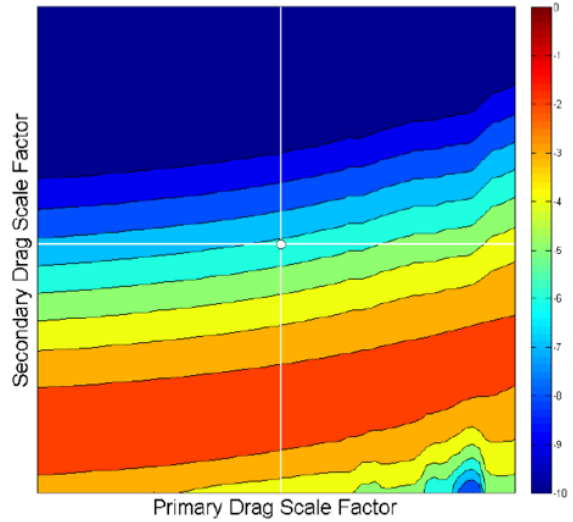
a.i. solutions

a.i. solutions, Inc.
10001 Derekwood Lane, Suite 215
Lanham, MD 20706

SWTS 09/03 23:38 UTC



SWTS 09/07 23:16 UTC

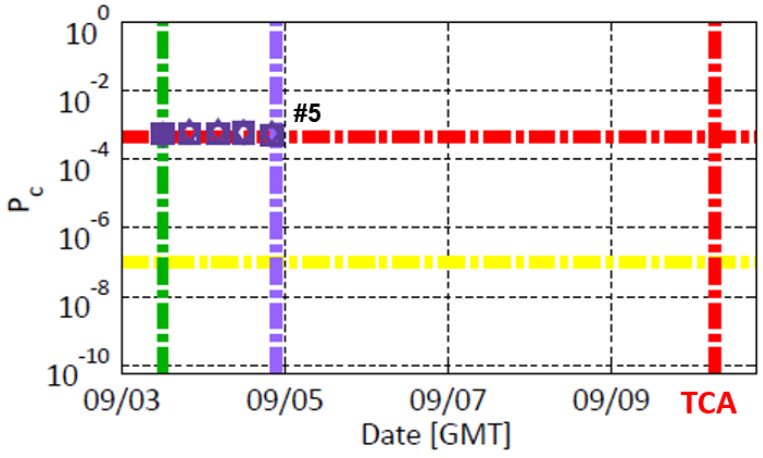


Case Study: Aura vs. 39858

(Tuesday, September 5, 2017) Slide 1 of 2

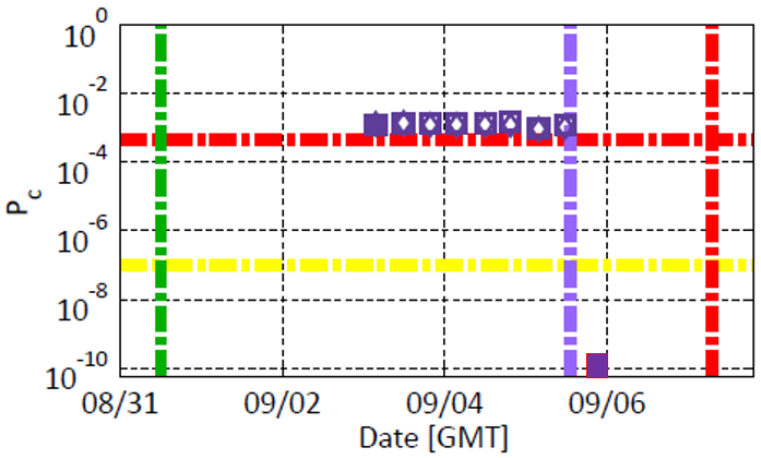
- **Aura Flight Support Team (FST) is monitoring a predicted high-risk close approach on Sunday, Sept 10th at 16:51:39 Greenwich Mean Time (GMT).**
  - Data Point #5: 5.4-days until TCA, no new tracking, Pc of 1 in 1758
- **At the same time the Aqua FST was actively monitoring an Aqua HIE with object 37494 with a time of closest approach (TCA) on Thursday, Sept 7th.**
  - Initial CARA notification: Sunday, Sept 3rd – poorly tracked secondary, Pc of 1 in 725
  - This was second Aqua HIE in a week (HIE with 82112 on 9/2), CME occurred 9/4
  - DAMs planned, DAM planning suspended Tuesday, September 5th around 1pm

CARA Screening Report – Tuesday 9/5 at 3:51am EDT



First time the conjunction appears in the CARA Screening Report – initial Pc is CARA RED at 1 in 1758

CARA Screening Report – Tuesday 9/5 at 11:57am EDT



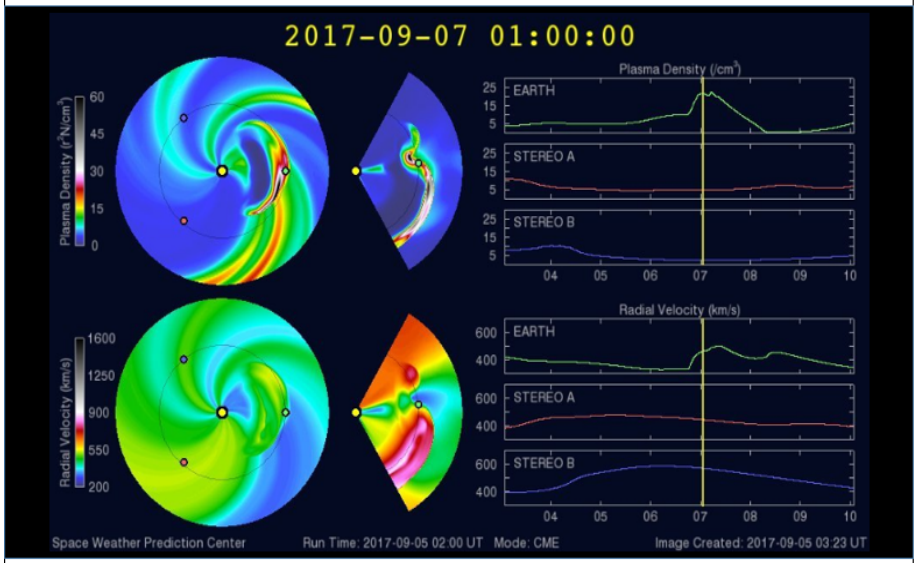
DAMs planned, maneuver planning suspended Tue, Sep 5th around 1pm after updated tracking dropped Pc to 0

Case Study: Aura vs. 39858

(Tuesday, September 5, 2017) Slide 2 of 2

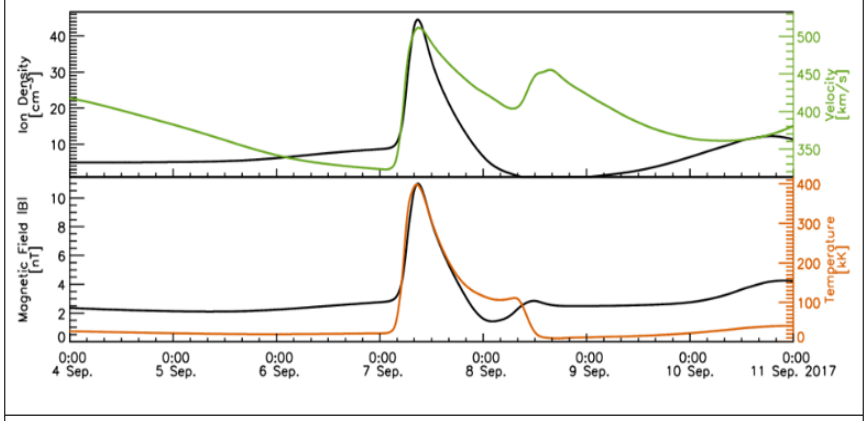
- **National Oceanic and Atmospheric Administration (NOAA) Space Weather Prediction Center (SWPC) prediction:**
  - Coronal Mass Ejection (CME) predicted to reach low earth orbiting (LEO) missions early on Thursday, September 7th
- **NASA/GSFC Space Weather Research Center (SWRC) CME prediction:**
  - Leading edge of the CME will reach missions near the earth early on Thursday, September 7th

NOAA WSA ENLIL Model CME Prediction



Coronal Mass Ejection (CME) prediction on Tue, Sep 5th at 05:02 GMT indicates CME Plasma Density peak on 9/7

NASA GSFC Space Weather Research Center



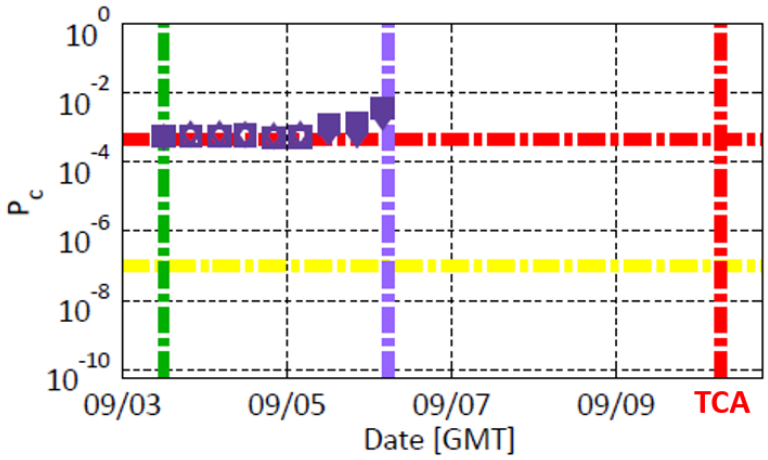
Tuesday, September 5th prediction for CME leading edge to reach missions near the earth early on September 7th

Case Study: Aura vs. 39858

(Wednesday, September 6, 2017) Slide 1 of 3

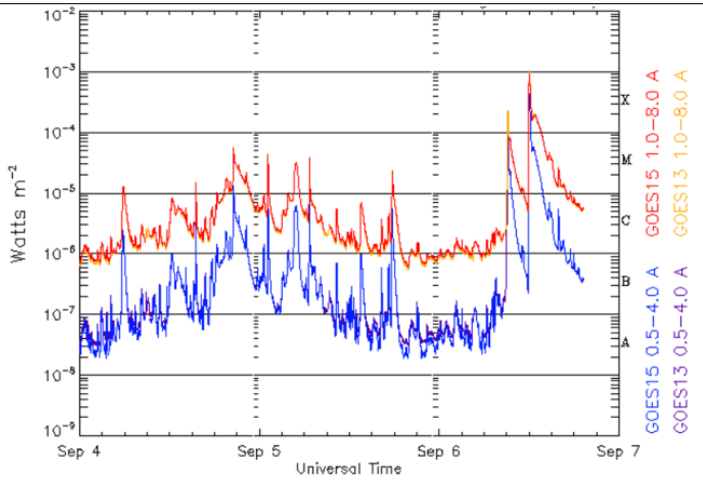
- **ESMO Collision Risk Management System (CRMS) begins generating Automated Maneuver Planning Reports (evening of Tuesday 9/5)**
  - Planning begins if within 5 days of TCA and Pc is greater than 1.0E-05 (1 in 100,000)
  - **Execute DAM if Pc greater than 4.4E-04 (Pc of 1 in 2272) – ESMO/CARA threshold**
- **An X9.3 class solar flare occurred at 12:02 GMT**
  - GOES X-Ray Flux clearly reflects the solar flare
- **Aura FST begins investigating Debris Avoidance Maneuver (DAM) options**
  - Near TCA or advance a planned 9/13 routine drag make up maneuver

CARA Screening Report – Wednesday 9/6 at 11:46am EDT



Probability of Collision (Pc) has steadily increased over the last 3 screening reports Pc is CARA RED at 1 in 494

Space Weather – GOES Xray Flux (1-minute data)



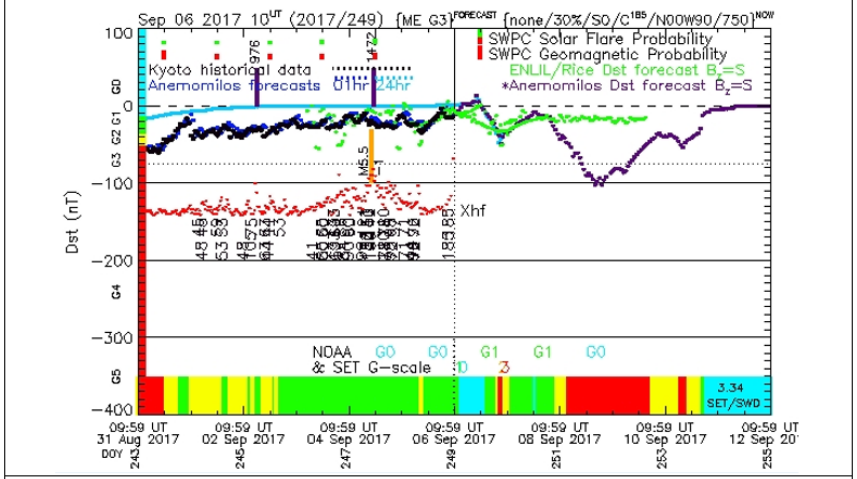
Updated September 6, 2017 at 19:16:12 UTC
NOAA/SWPC Boulder, CO USA

Case Study: Aura vs. 39858

(Wednesday, September 6, 2017) Slide 2 of 3

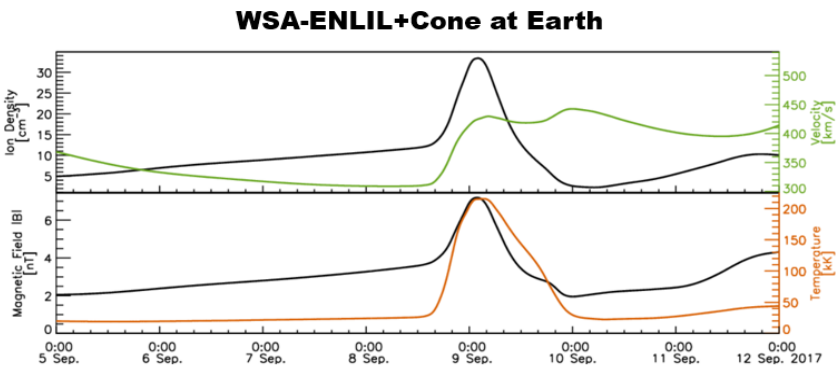
- **Space Environment Technologies (SET) SpaceWx Alert Monitor Anemomilos Solar Storm Prediction Model Disturbance Storm Time (Dst) history and forecast (Credit: http://spacewx.com)**
  - Dst predicted to be at storm levels on Friday, September 9th
- **NASA/GSFC Space Weather Research Center (SWRC) CME prediction:**
  - Indicates the leading edge of the CME will reach missions near the earth early on Friday, September 8th at 18:27 +/- 7-hours (2nd CME)

Space Weather – SET SpaceWx Alert Monitor Dst



September 6th at 10 UT – Dst History & Forecast
Dst predicted to go below JSpOC threshold of -75 nT

NASA GSFC Space Weather Research Center



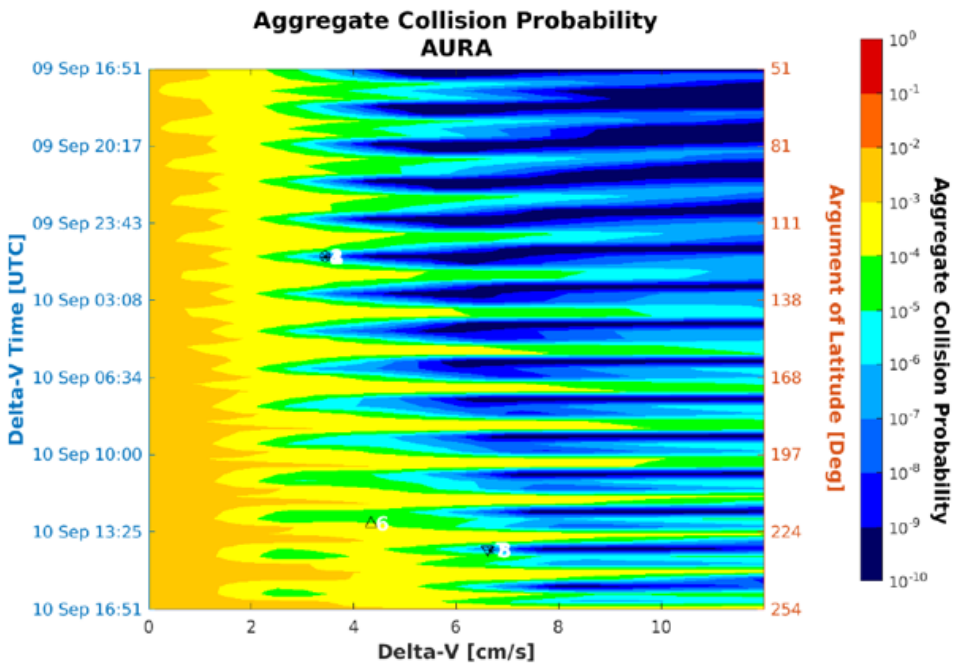
Wednesday, September 6th prediction for CME leading edge to reach missions near the earth late on September 8th

Case Study: Aura vs. 39858

(Wednesday, September 6, 2017) Slide 3 of 3

- **ESMO Collision Risk Management System (CRMS) generating Automated Maneuver Planning Reports with multiple DAM options**
  - Optimum unconstrained maneuver
  - Constrained maneuvers based on mission requirements and constraints

SpaceNav Collision Risk Management System (CRMS)



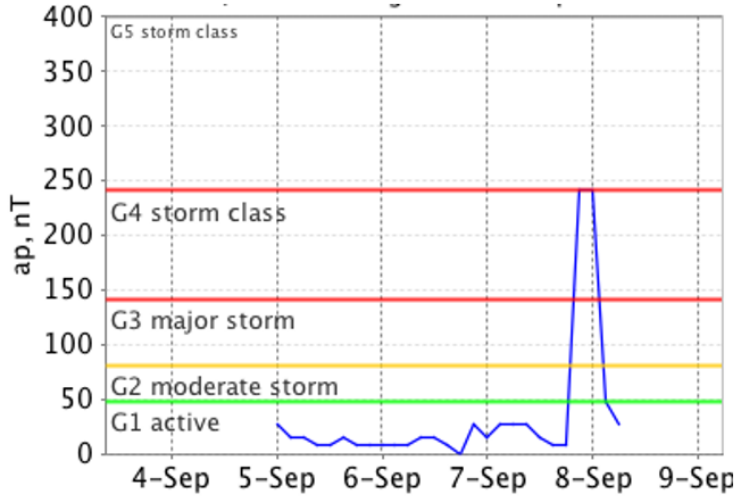
Wednesday, September 6, 2017
Automated Maneuver Planning Report

Case Study: Aura vs. 39858

(Thursday, September 7, 2017) Slide 1 of 2

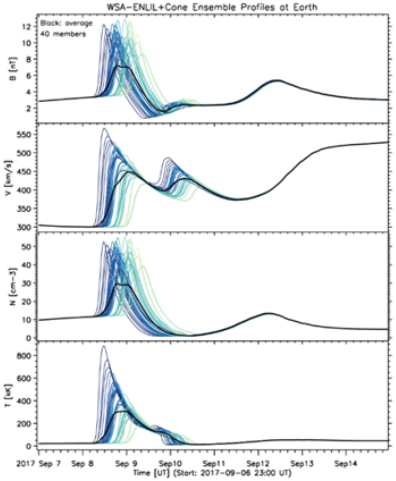
- **NOAA Space Weather Prediction Center (SWPC) Geomagnetic Index (Ap) history:**
  - Ap reached G4 Storm levels late on Thursday, September 7th
- **NASA/GSFC Space Weather Research Center (SWRC) CME prediction:**
  - Indicates the leading edge of the CME will reach missions near the earth on September 8th

Space Weather – NOAA/SWPC Geomagnetic Index Ap



Thursday, September 7th
Ap Index reached G4 Storm Class late on Sep 7th

NASA GSFC Space Weather Research Center



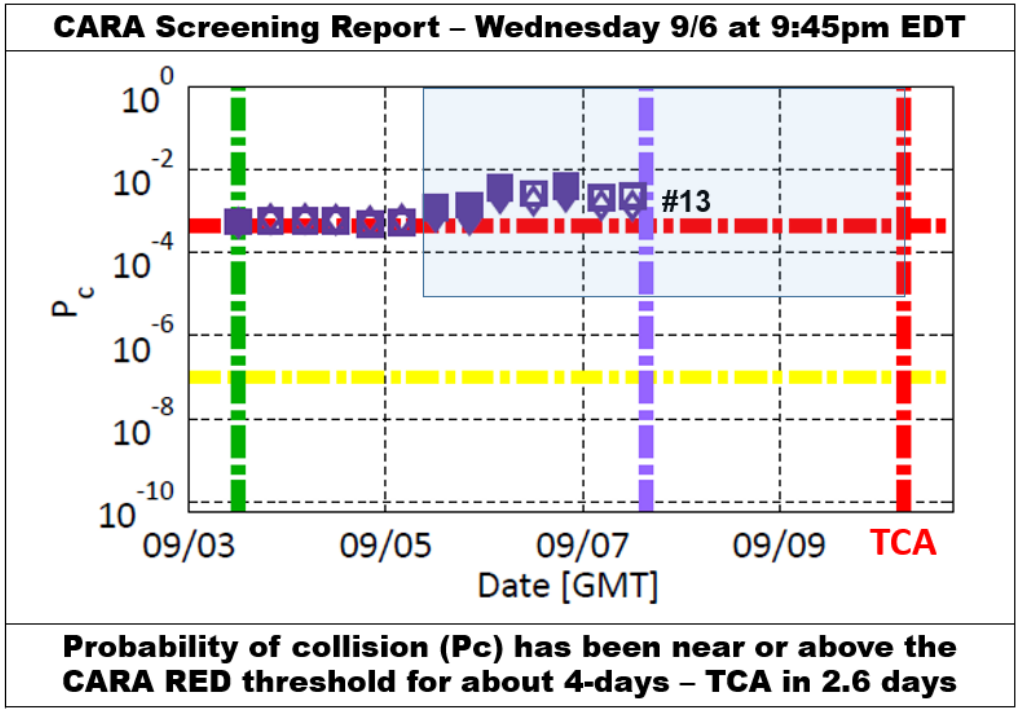
Based on heliospheric ensemble modeling carried out at NASA GSFC Space Weather Research Center, it is estimated that the CME may impact NASA missions near Earth. Out of 40 ensemble members (see notes section), 40 (100%) indicate impact at NASA missions near Earth. Ensemble simulations indicate that the leading edge of the CME will reach NASA missions near Earth between about 2017-09-08T06:58Z and 2017-09-09T02:02Z (average arrival 2017-09-08T15:48Z). The ensemble-based forecast indicates that there is a 87% chance for the maximum Kp index to be in the 4-6 range (below minor to moderate).

Thursday, September 7th prediction for CME leading edge to reach missions near the earth on September 8th

Case Study: Aura vs. 39858

(Thursday, September 7, 2017) Slide 2 of 2

- **Data Point #13: 2.6-days until TCA, no new tracking, Pc of 1: 743**

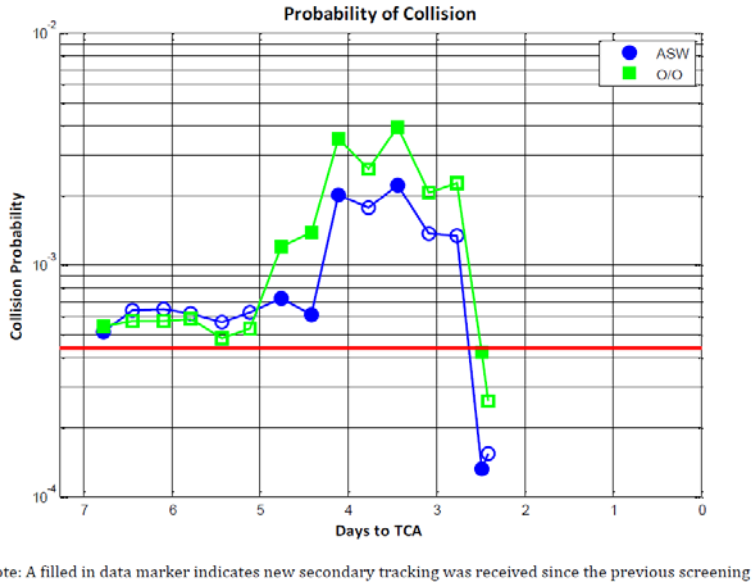


- **9:35am EDT: CARA notified the FOT of the Aura High Interest Event (HIE)**
  - Estimated ASW Pc is 2.22E-3 (1 in 450), Predicted ASW miss distance of 2733 meters
  - Secondary object marginally tracked at just over 1 track per day
  - Relatively large uncertainties in the in-track and cross-track directions

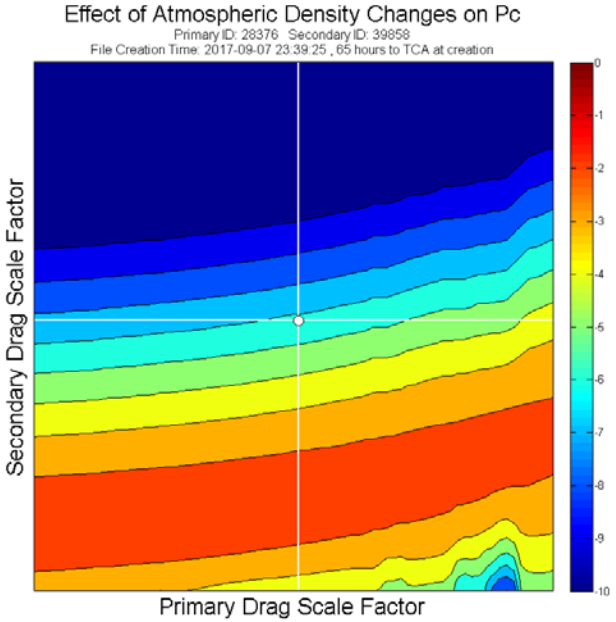
Case Study: Aura vs. 39858

(Friday, September 8, 2017) Slide 1 of 3

- **10am EDT: CARA Conducts first HIE Briefing for the Aura FST**
  - Data Point #15: Estimated ASW Pc is 1.54E-4 (1 in 6493) – CARA YELLOW
  - Dst value has reached the -75nT threshold for Solar Storm modeling
  - CARA Space Weather Trade Space Tool inconclusive
  - Continue to monitor, perform DAM if the estimated Pc increases to RED threshold



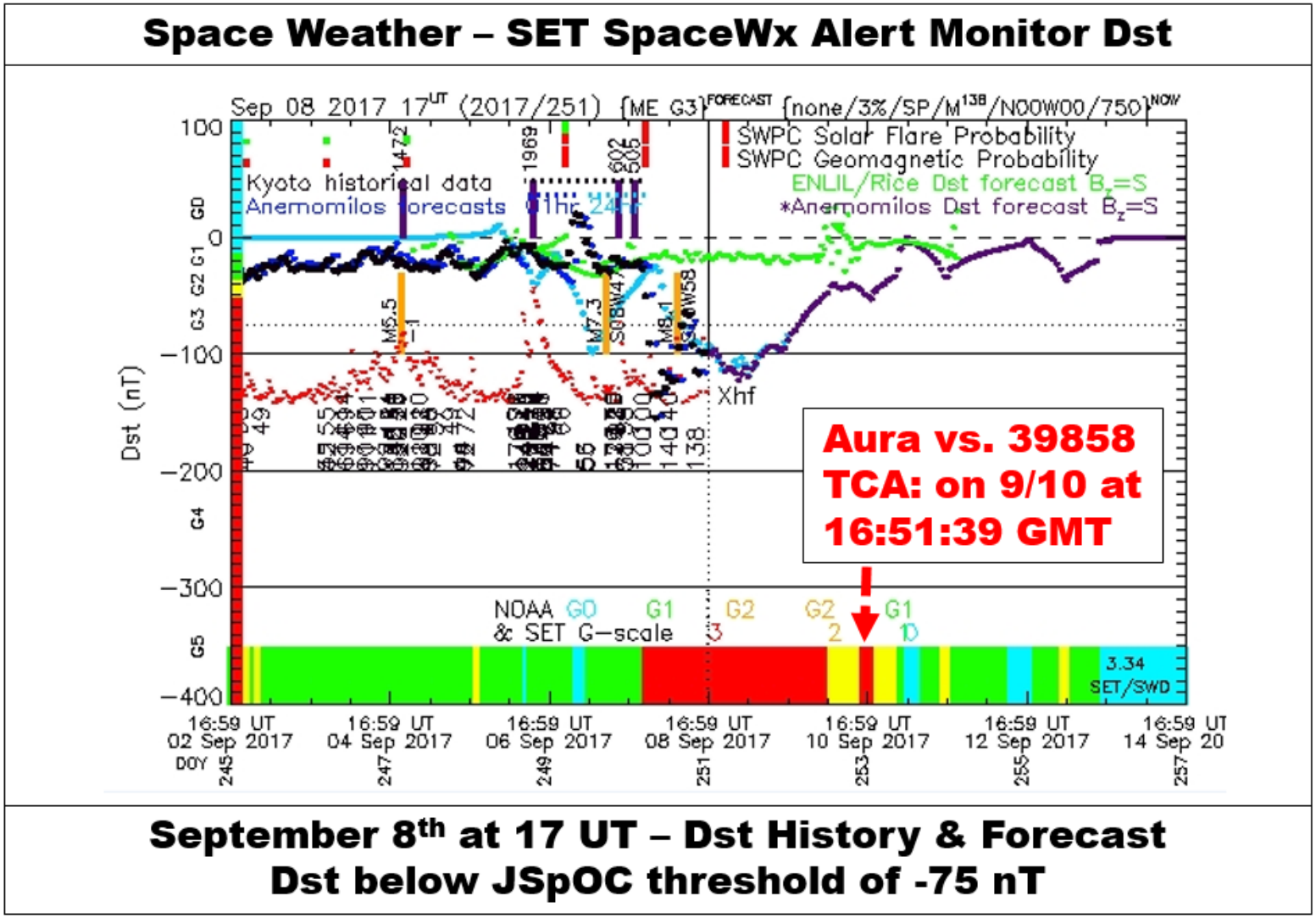
Note: A filled in data marker indicates new secondary tracking was received since the previous screening



- **4pm EDT: CARA Conducts second HIE Briefing for the Aura FST**
  - Data Point #16: Updated tracking reduced the Pc to 0
  - Continue to monitor for changes

Case Study: Aura vs. 39858

(Friday, Sept 8, 2017) Slide 2 of 3 (Credit: http://spacewx.com)

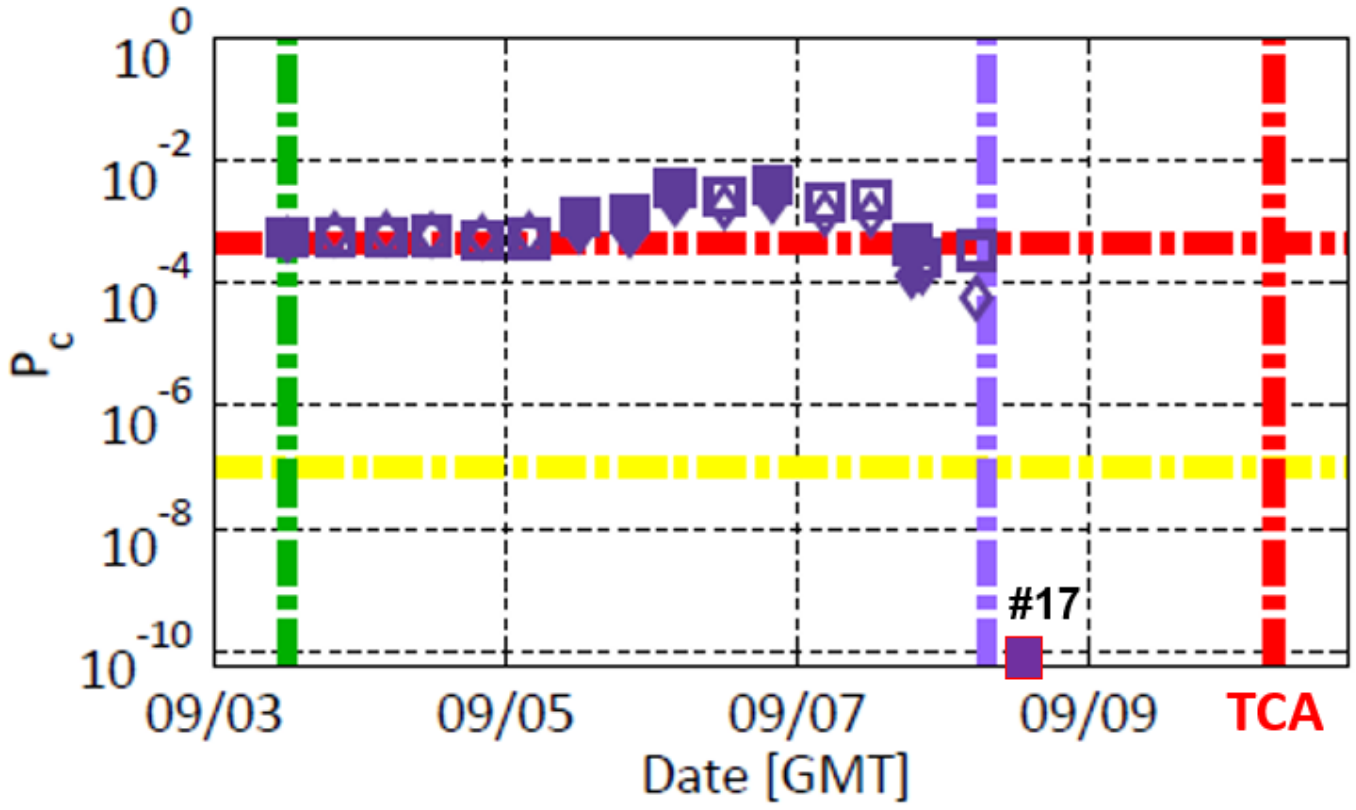


Case Study: Aura vs. 39858

(Friday, September 8, 2017) Slide 3 of 3

- **Data Point #17: 1.8-days until TCA, updated tracking, Pc dropped off**

CARA Screening Report – Friday 9/8 at 5:37pm EDT



Probability of collision (Pc) dropped to zero over the course of the last 3 screening reports with updated tracking

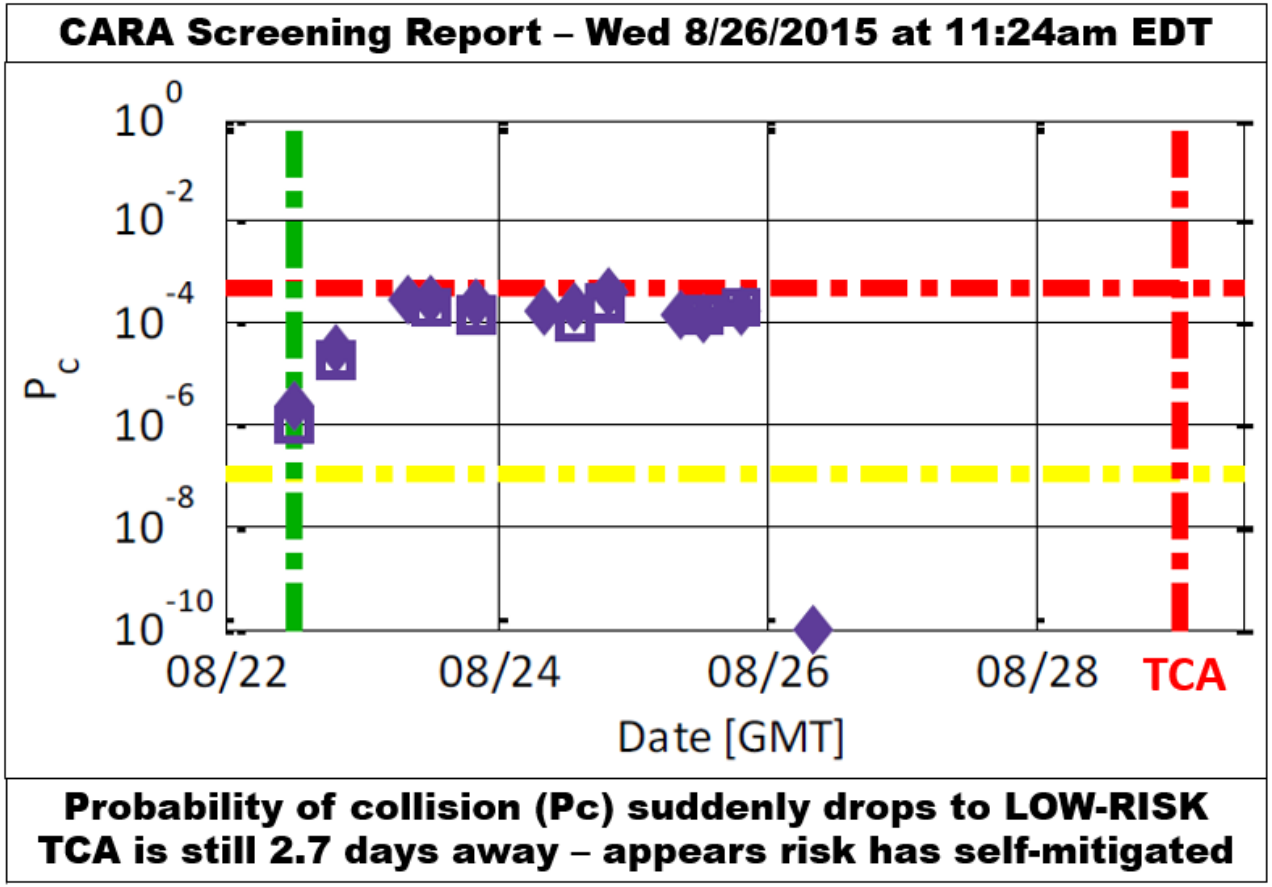
What, Me Worry

http://d3fhkv6xpescls.cloudfront.net/blog/wp-content/uploads/2011/04/Alfred-E-Newman-299x300.gif

Case Study: Aura vs. 89477

(TCA: 2015-08-29 at 07:51:15 GMT) Slide 1 of 4

- **August 29, 2015 Aura predicted close approach was particularly challenging High Interest Event (HIE).**
- **Similar to Aura vs. 39858 HIE?**

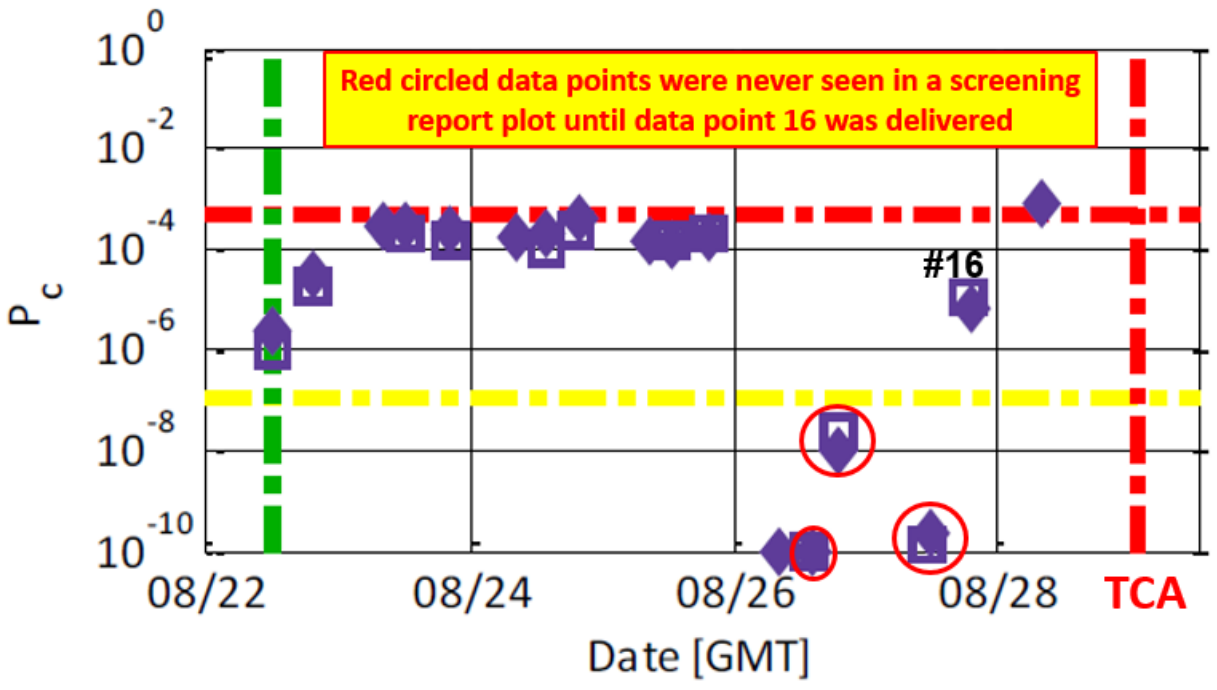


Case Study: Aura vs. 89477

(TCA: 2015-08-29 at 07:51:15 GMT) Slide 2 of 4

- **Late notice HIE with dramatic change to the risk highlights the need to be able to detect changes and respond faster.**
- **FST planned, built and screened potential DAMs (Prime and Backup)**

CARA Screening Report – Fri 8/28/2015 at 11:51am EDT

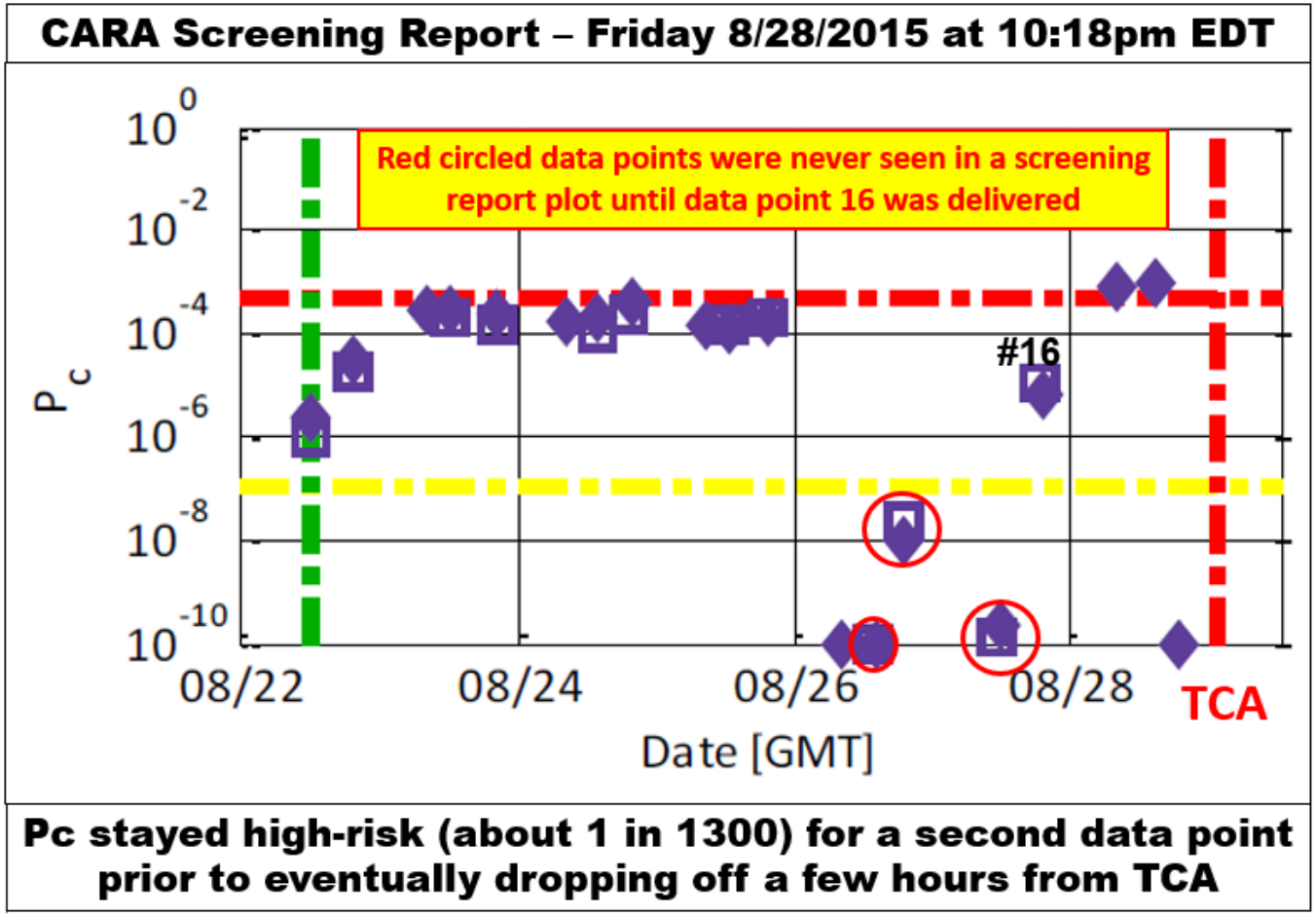


Pc dramatically increases with only 16-hours to TCA during period of intense solar and geomagnetic activity

Case Study: Aura vs. 89477

(TCA: 2015-08-29 at 07:51:15 GMT) Slide 3 of 4

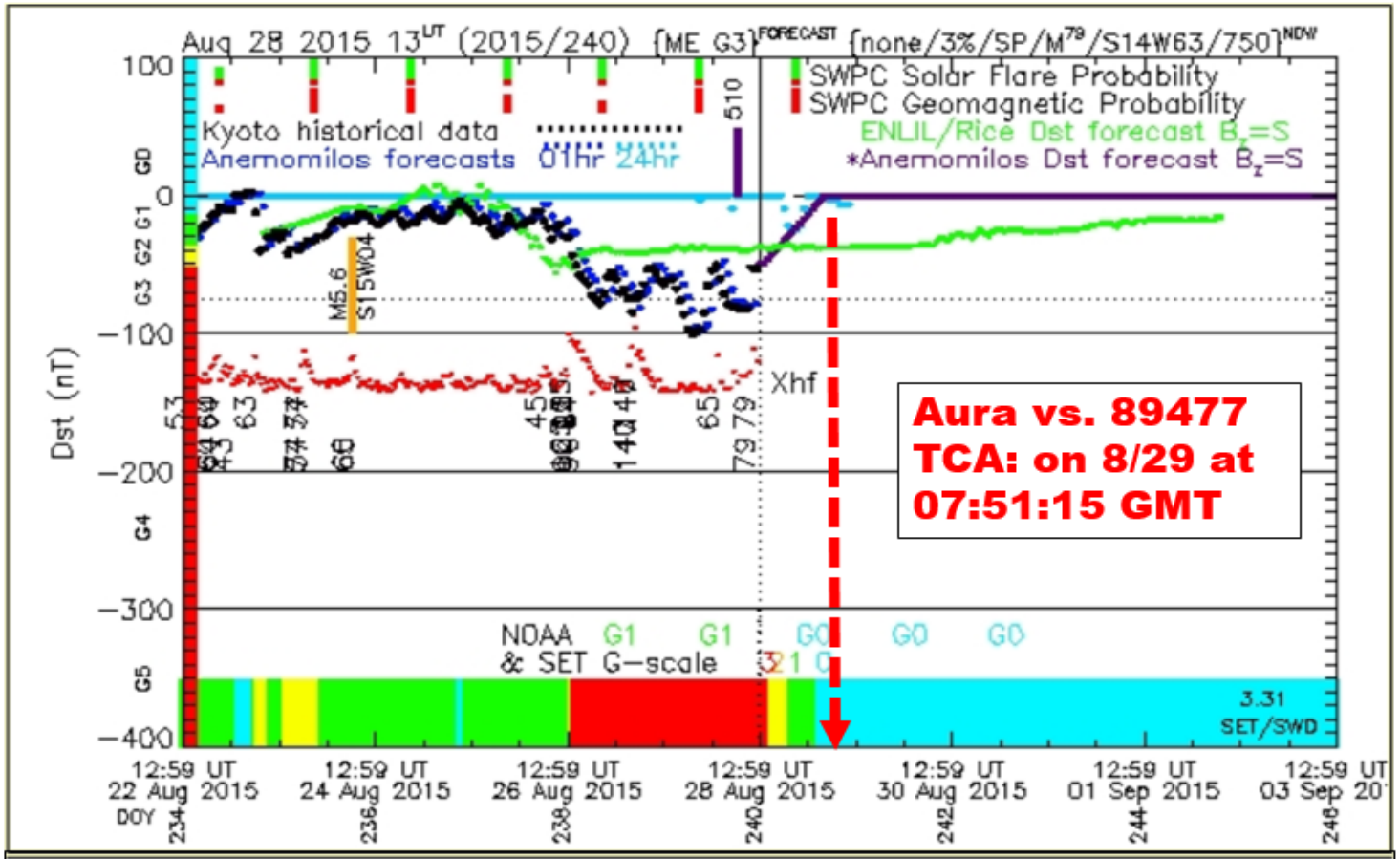
- **Updated tracking just hours prior to the conjunction resulted in the risk rolling off after the prime burn opportunity had been waived-off to allow more time to collect and analyze the data.**



Case Study: Aura vs. 89477

(TCA: 2015-08-29 at 07:51:15 GMT) Slide 4 of 4

Space Weather – SET SpaceWx Alert Monitor Dst



Intense solar and geomagnetic activity resulted in changes in predicted drag that changed predicted miss distances & probability-of-collision (Pc). Pc peaked at about 1 in 1300

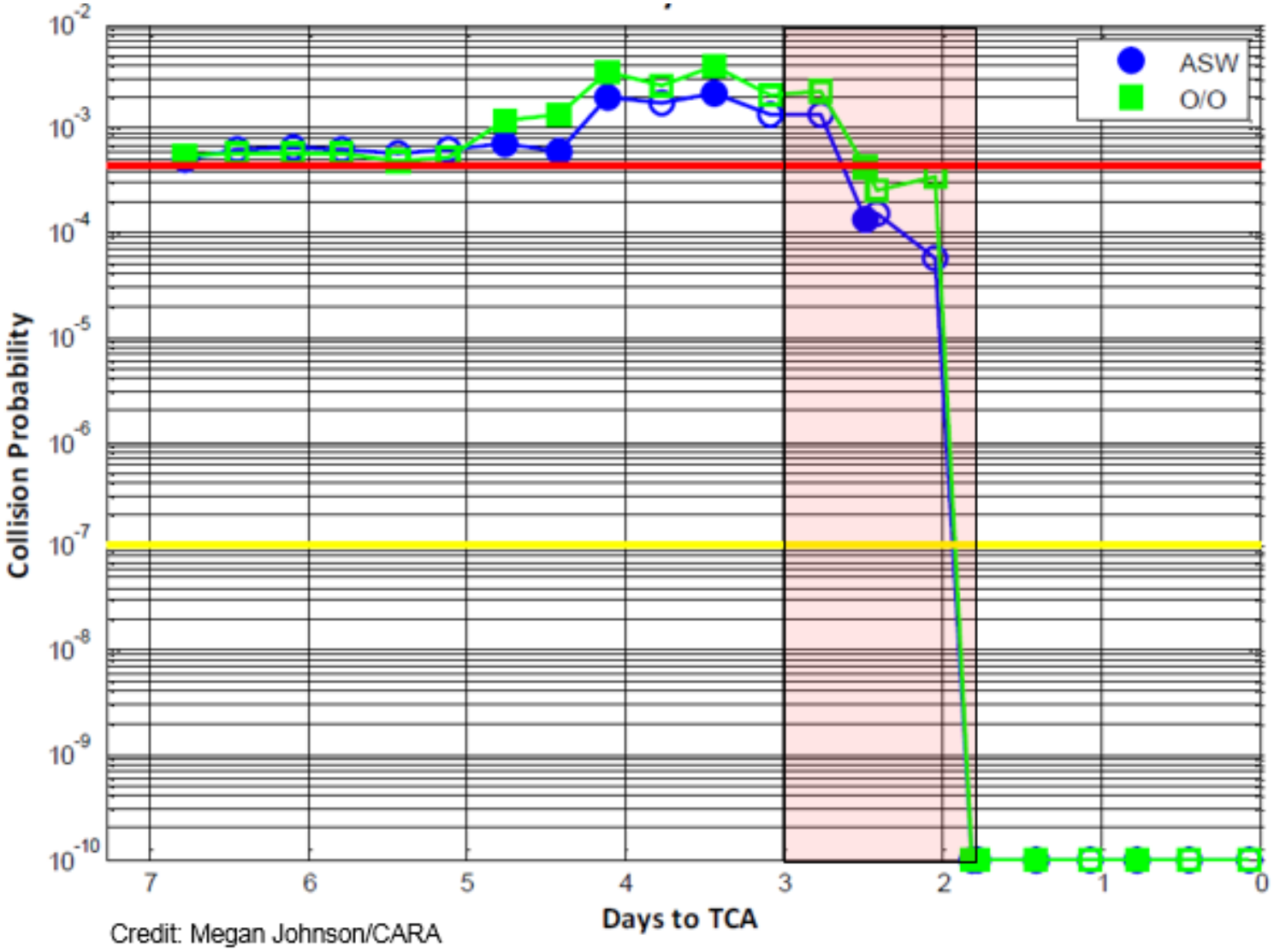
Credit: http://spacewx.com

https://i.ytimg.com/vi/7EswDwY-944/hqdefault.jpg

Aura vs. 39858 Case Study

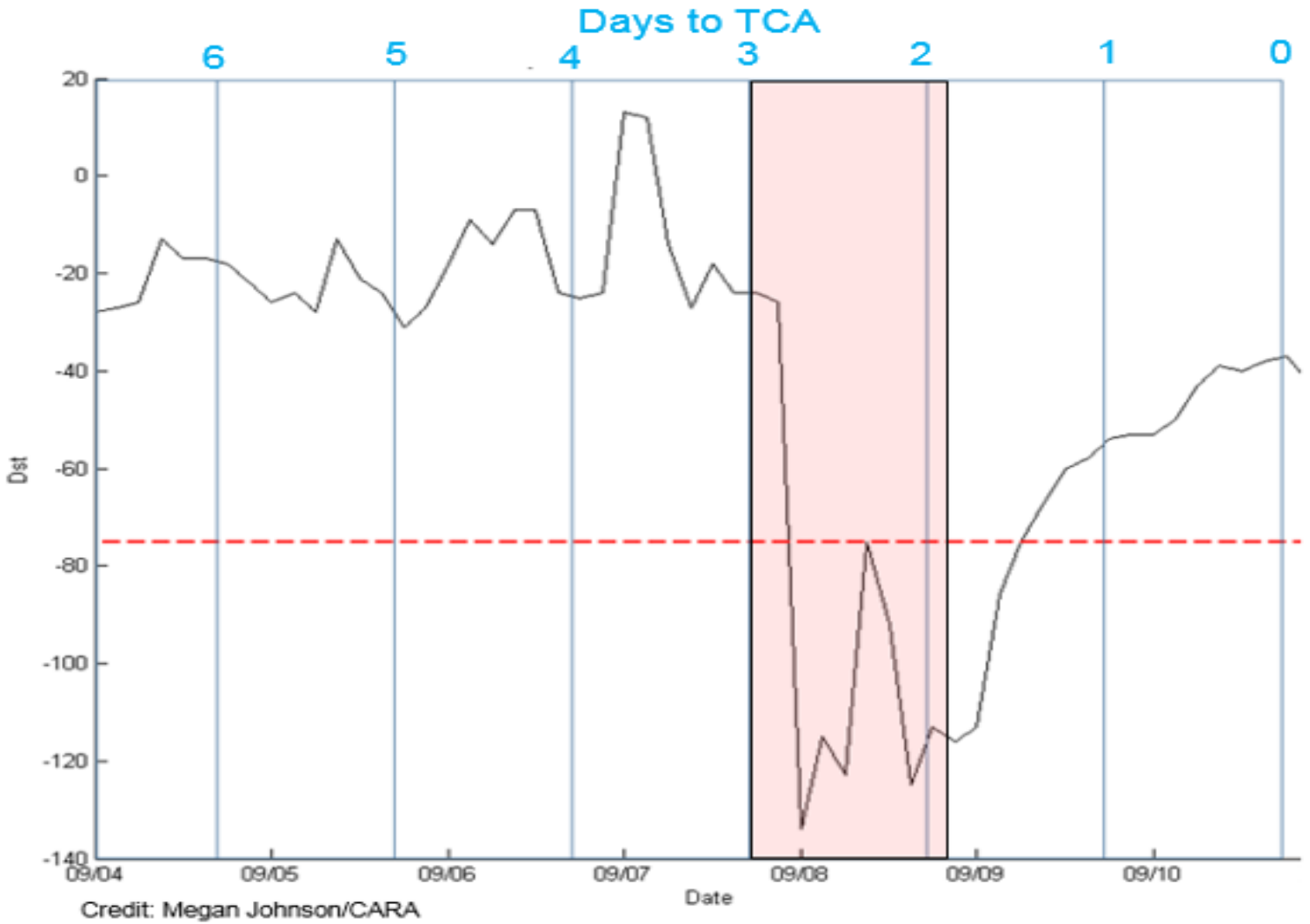
Case Study: Aura vs. 39858

Pc History



Case Study: Aura vs. 39858

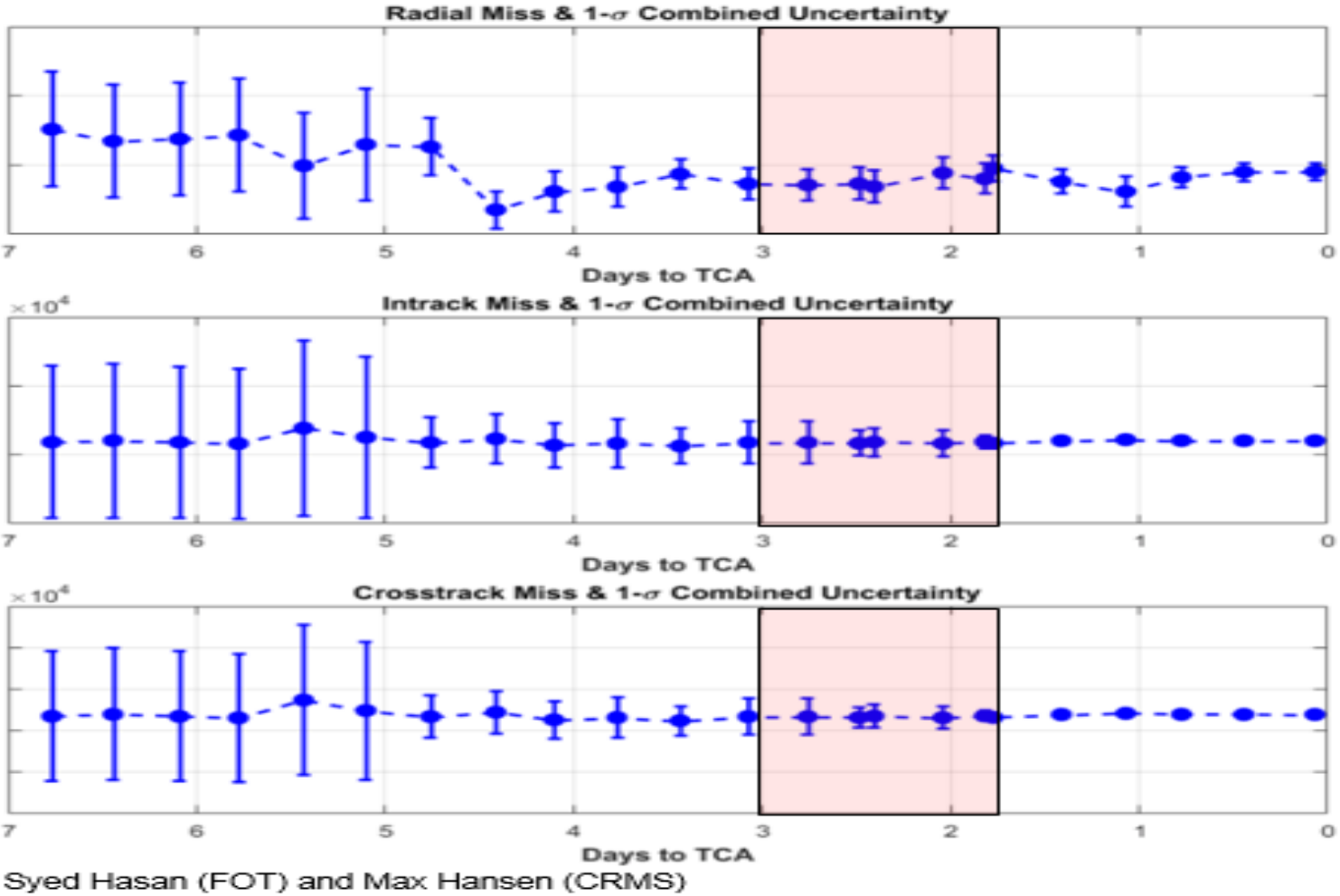
Dst History



Case Study: Aura vs. 39858

Predicted Miss Distances and Uncertainties

Why don't we see changes in the uncertainties?



Syed Hasan (FOT) and Max Hansen (CRMS)

Aura vs. 39858 Summary

(TCA: 2017-09-10 at 16:51:39 GMT)

- **In Hindsight: The September 10th Aura predicted close approach turned out to be not as challenging of an High Interest Event (HIE) as it appeared it might be as it was developing.**
- **Changes in the conjunction resulted in a high-risk (1 in 743) with only about 2.6-days until time of close approach (TCA).**
- **The ESMO Flight Support Team (FST) did their usual superb job and were prepared to execute a debris avoidance maneuver.**
  - Overlapped with Aqua HIE on September 7, 2017
- **Updated tracking resulted in the risk rolling off.**
- **Overall the Aura HIE was similar to a number of other short-notice HIEs some of which also included significant Space Weather.**
  - Terra: June 24, 2015, December 19, 2015
  - Aqua: September 2, 2017, September 7, 2017
  - Aura: September 3, 2013, February 2, 2014, August 29, 2015

Some things that worked

- Flight Operations Team (FOT) Collision Avoidance Engineer notified the Aura Mission Director during their weekly tag-up meeting that he was monitoring a high-risk Aura conjunction that just started appearing in the CARA Screening Reports (by design at 5.5-days to TCA) but had been in the ESMO Collision Risk Management System (CRMS) reports since first detected (about 7-days from TCA)
- Mission Director included the conjunction in the Weekly Top Ten Issues reviewed with the flight support team on Tuesday
- Various Space Weather alerts and warnings were issued starting on Monday, September 4th (CME)
- Flight Support Team monitoring Space Weather (Dst, Ap, …)
- Flight Support Team explored various maneuver options, that included possibly moving up a planned routine drag make up maneuver to Saturday, September 9th and were prepared to executed debris avoidance maneuver if necessary

Some Questions

- During periods of intense solar activity what changes are being made at the JSpOC with their atmospheric density models?
- How long are the changes modeled for?
- How frequently are updates made to the models?
- When are the models returned to “normal”?
- What magnitude of changes can be expected in predicted miss distances, covariance and probability of collision?

Bottom Line: We need a better understanding of space weather effects on predicted high-risk conjunctions.

Questions

Abbreviations / Acronyms List

ASW –	Astrodynamics Workstation
CA –	Conjunction Assessment
CARA –	Conjunction Assessment Risk Analysis
CNES –	Centre national d'études spatiales
CRMS –	Collision Risk Management System
DAM –	Debris Avoidance Maneuver
DMUM –	Drag Make-up Maneuver
EDT –	Eastern Daylight Time
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
km –	kilometer
MLT –	Mean Local Time
MMOD –	Micrometeorite Orbital Debris
MMS –	Mission Management System
MOWG –	Mission Operations Working Group
MTS –	Maneuver Trade Space
NASA –	National Aeronautics & Space Administration
NOAA –	National Oceanic and Atmospheric Administration
Pc –	Probability of Collision
RMM –	Risk Mitigation Maneuver
SWRC –	Space Weather Research Center (NASA GSFC)
SWPC –	Space Weather Prediction Center (NOAA)
TBD –	To Be Determined
TCA –	Time of Closest Approach
UT –	Universal Time
UTC –	Coordinated Universal Time
WSA-ENLIL –	Space weather prediction model that is named after Wang-Sheeley-Arge (WSA), three important scientists in space weather, and the Sumerian god of winds and storms (ENLIL)