NASA Space Exploration & Space Weather Workshop

September 26-27, 2017

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

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Satellites & Space Weather

- **Effects of space weather on spacecraft systems are well documented** (Ref: NOAA Space Weather Prediction Center)
  - Surface Charging/Electrostatic Discharge (ESD)
  - Deep dielectric or bulk charging
  - Single Event Upset (SEU)/Single Event Latch-up (SEL)
    - Solar proton events (SPEs)
    - Galactic cosmic rays (GCRs)
  - Spacecraft drag
  - Total dose effects
  - Solar radio frequency interference and telemetry scintillation
  - Debris
  - Spacecraft orientation
  - Photonics noise
  - Materials degradation
  - Meteorite impact
- **But what do we know about the effects of space weather modeling on conjunction assessment and collision avoidance?**

Conjunction Assessment & Collision Avoidance

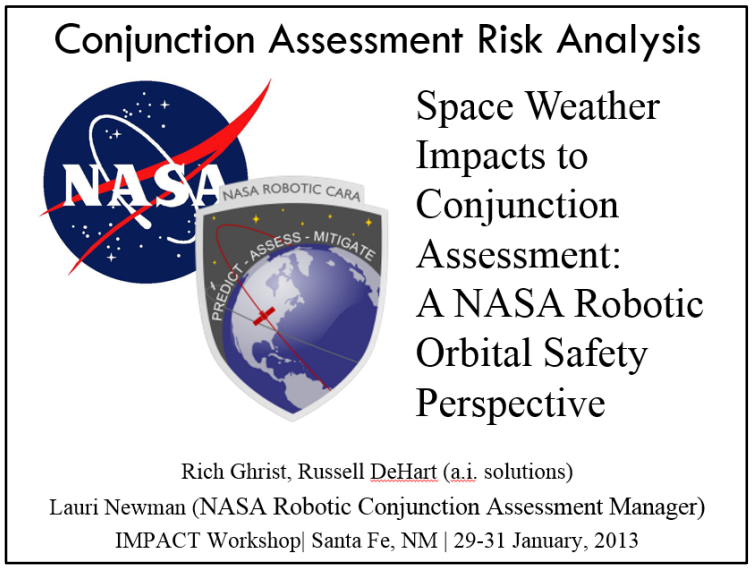
Space Weather Events around Time of Closest Approach

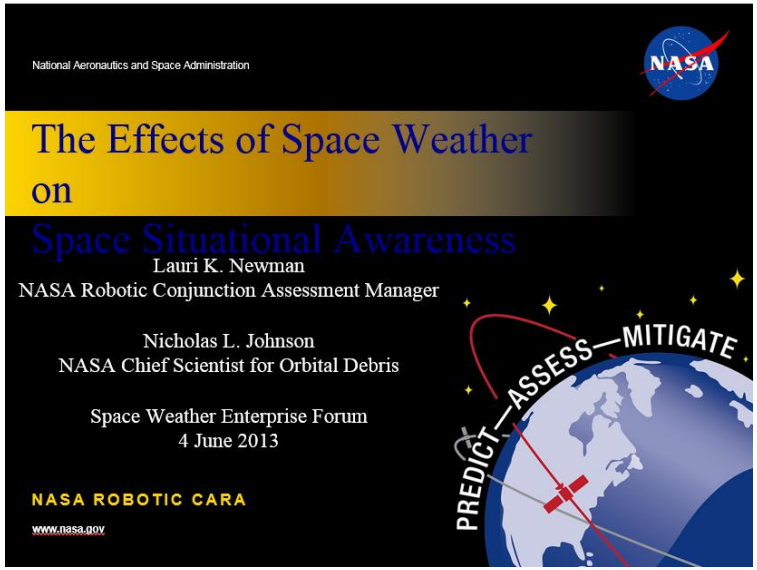
- **Joint Space Operations Center (JSpOC) space weather predictions based on:**
  - Jacchia-Bowman 2008 (JB08)
  - High Accuracy Satellite Drag Model (HASDM)
  - Anemomilos Solar Storm Prediction Model Disturbance Storm Time (Dst)
- **Typically Debris Avoidance Maneuver (DAM) planning begins ~24 to 72 hours prior to Time of Closest Approach (TCA) using the;**
  - Latest tracking data
  - 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)
  - Flight Dynamics Team (FDT)
  - Conjunction Assessment Risk Analysis (CARA) Team
  - JSpOC GSFC Orbital Safety Analyst (OSA)
- **Designed to allow sufficient time for the FST to work 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 and magnitude of Solar Events prior to TCA complicate evaluation in determining if a DAM is warranted or could possibly make matters worse (typically plus or minus hours)

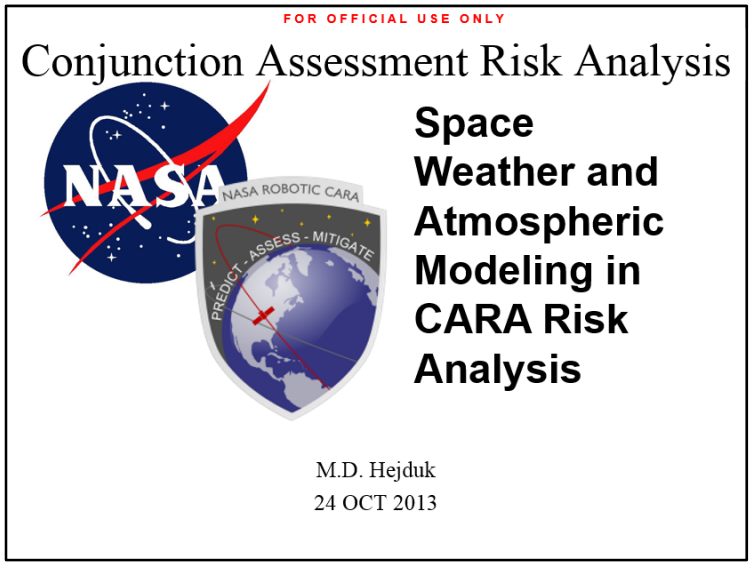
ESMO experience with Space Weather

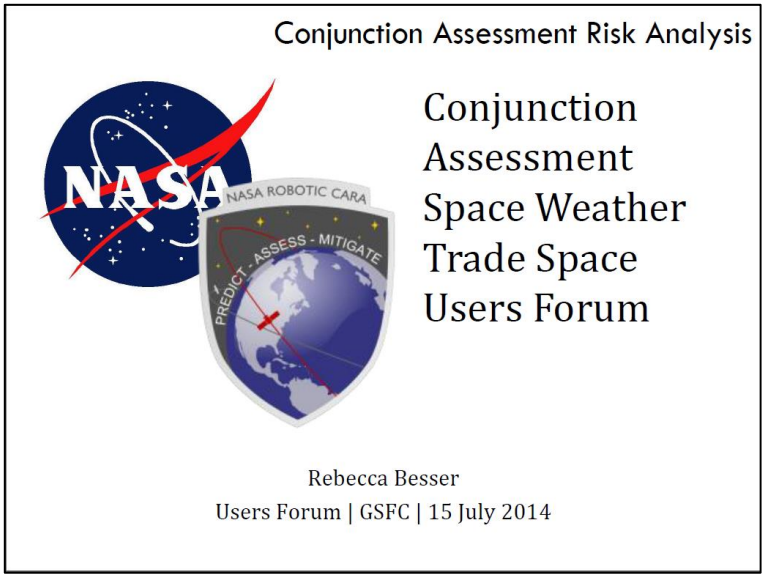
- **Some examples from Earth Science Constellation (ESC) history**
- **2011: CloudSat high interest event (HIE) with radial miss changing signs on successive updates (any space weather?)**
  - ESMO raised concerns about managing HIEs during solar activity
- **2014: 6th GSFC Space Weather Workshop**
  - Case Study: Aura vs. 35380 TCA: 2014-02-16
    - > CME predicted to arrive about 30-hours prior to planned potential DAM
    - > DAM waived off Saturday, February 12th
- **2015: 7th GSFC Space Weather Workshop**
  - Case Study: Aura vs. 89477 TCA: 2015-08-28
    - > Short-notice, 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 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**
  - CARA Conjunction Assessment Late-Notice HIEs (Hejduk & Pachura)

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

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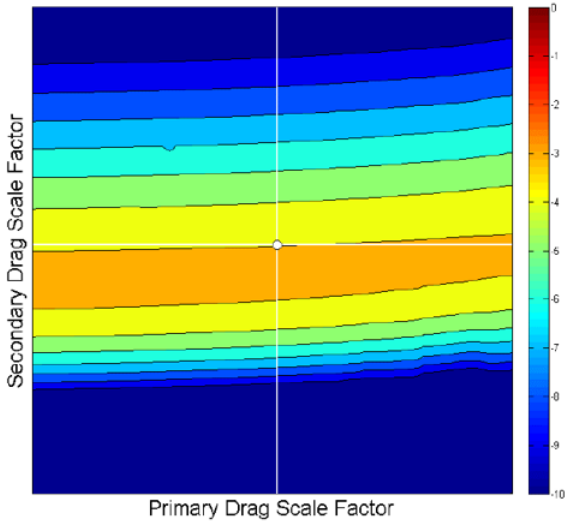
SWTS 09/03 23:38 UTC



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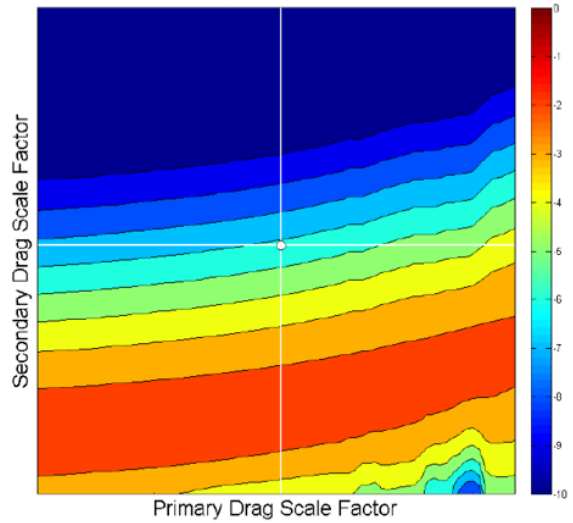
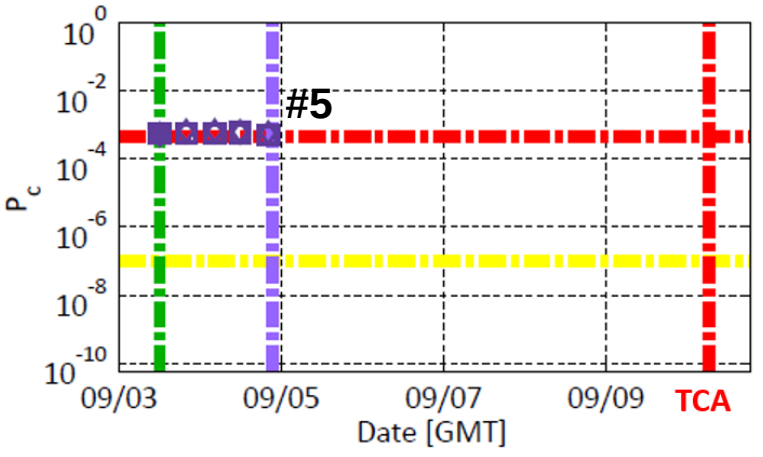


Case Study: Aura vs. 39858

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

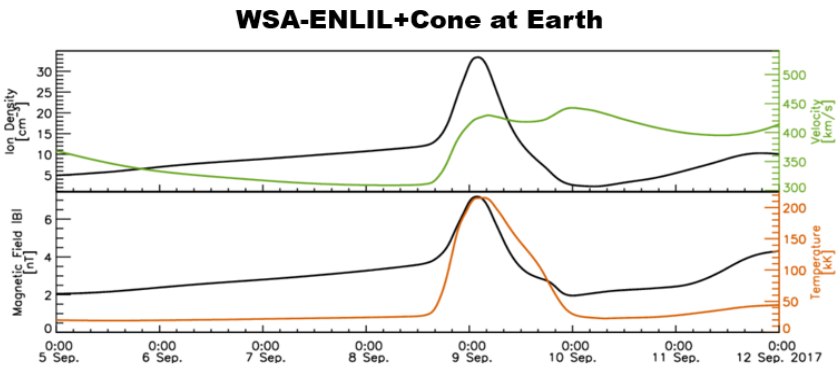
- **September 5th: Aura Flight Support Team (FST) is monitoring a predicted high-risk close approach for EOS Aura on Sunday, September 10th at 16:51:39 Greenwich Mean Time (GMT).**
- **5.4-days until TCA (data point #5, no new tracking, Pc of 1 in 1758)**
- **At the same time, ESMO EOS FST actively monitoring an Aqua HIE with a time of closest approach (TCA) on Thursday, September 7th .**
  - Initial CARA notification: Sunday, September 3rd – poorly tracked secondary & a CME has occurred
  - DAM Planning suspended: Tuesday, September 5th around 1pm

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



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

NASA GSFC Space Weather Research Center



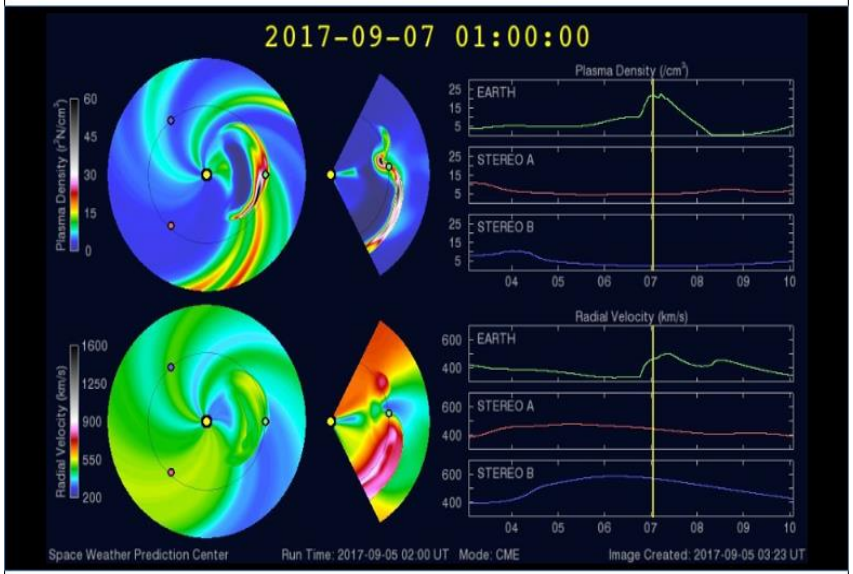
Wednesday, September 6th prediction for CME leading edge to reach missions near the earth late on September 8th

Case Study: Aura vs. 39858

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

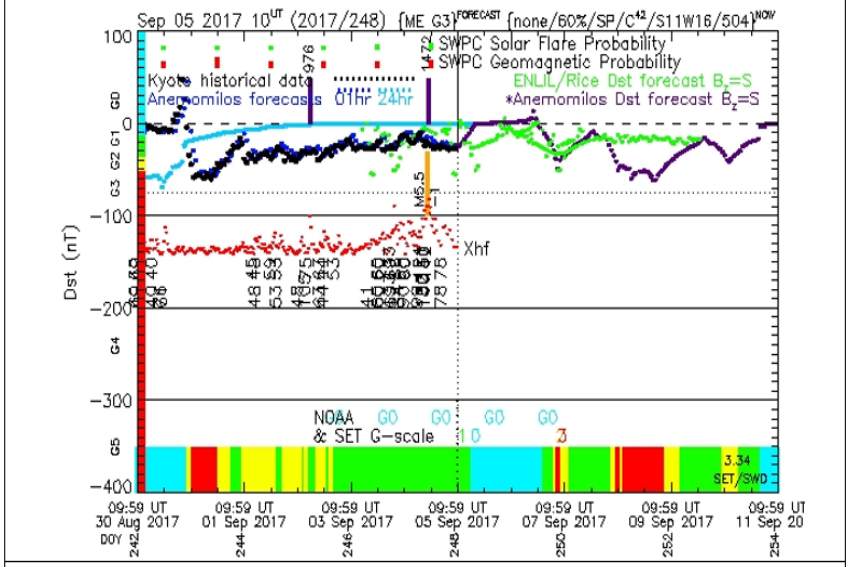
- **September 5th: Coronal Mass Ejection (CME) predicted to reach low earth orbiting (LEO) missions on 9/7 at 18:27 +/- 7-hours (1st CME)**
- **Prediction from National Oceanic and Atmospheric Administration (NOAA) Space Weather Prediction Center (SWPC)**
- **Disturbance Storm Time (Dst) history and forecast from Space Environment Technologies (SET) SpaceWx Alert Monitor Anemomilos Solar Storm Prediction Model**

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

Space Weather – Dst History & Forecast



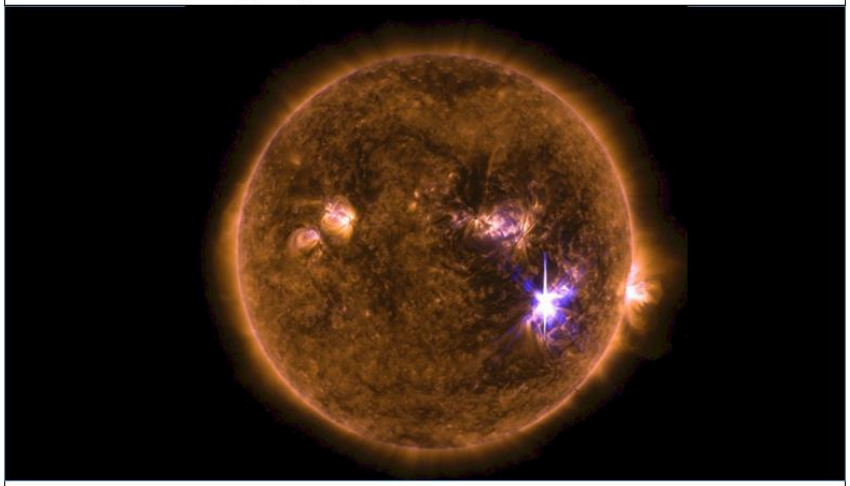
September 5th – Dst History & Forecast
Significant solar and geomagnetic activity occurring

Case Study: Aura vs. 39858

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

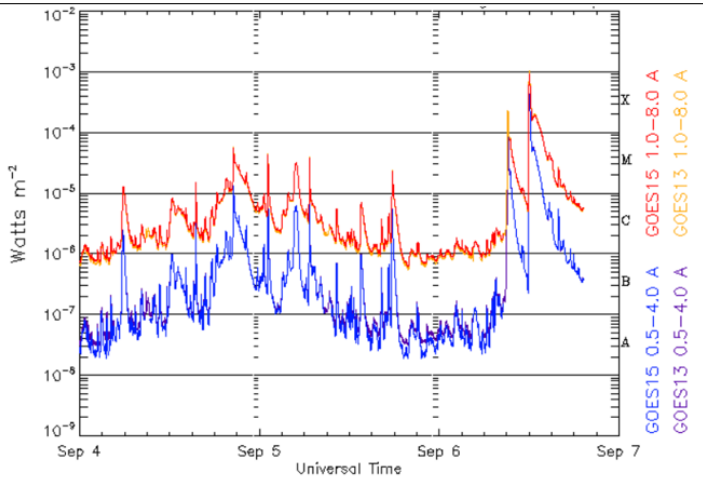
- **September 6th: An X9.3 class solar flare had occurred and GOES X-Ray Flux clearly reflects the solar flare**
- **Aura FST begins to investigate Debris Avoidance Maneuver (DAM) options**
  - Near TCA or advance a planned routine drag make up maneuver
- **ESMO Collision Risk Management System (CRMS) begins generating Automated Maneuver Planning Reports (evening of 9/5)**
  - Begins planning if 5 days from 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**

Wednesday, September 6th X9.3 class solar flare



NASA Solar Dynamics Observatory

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

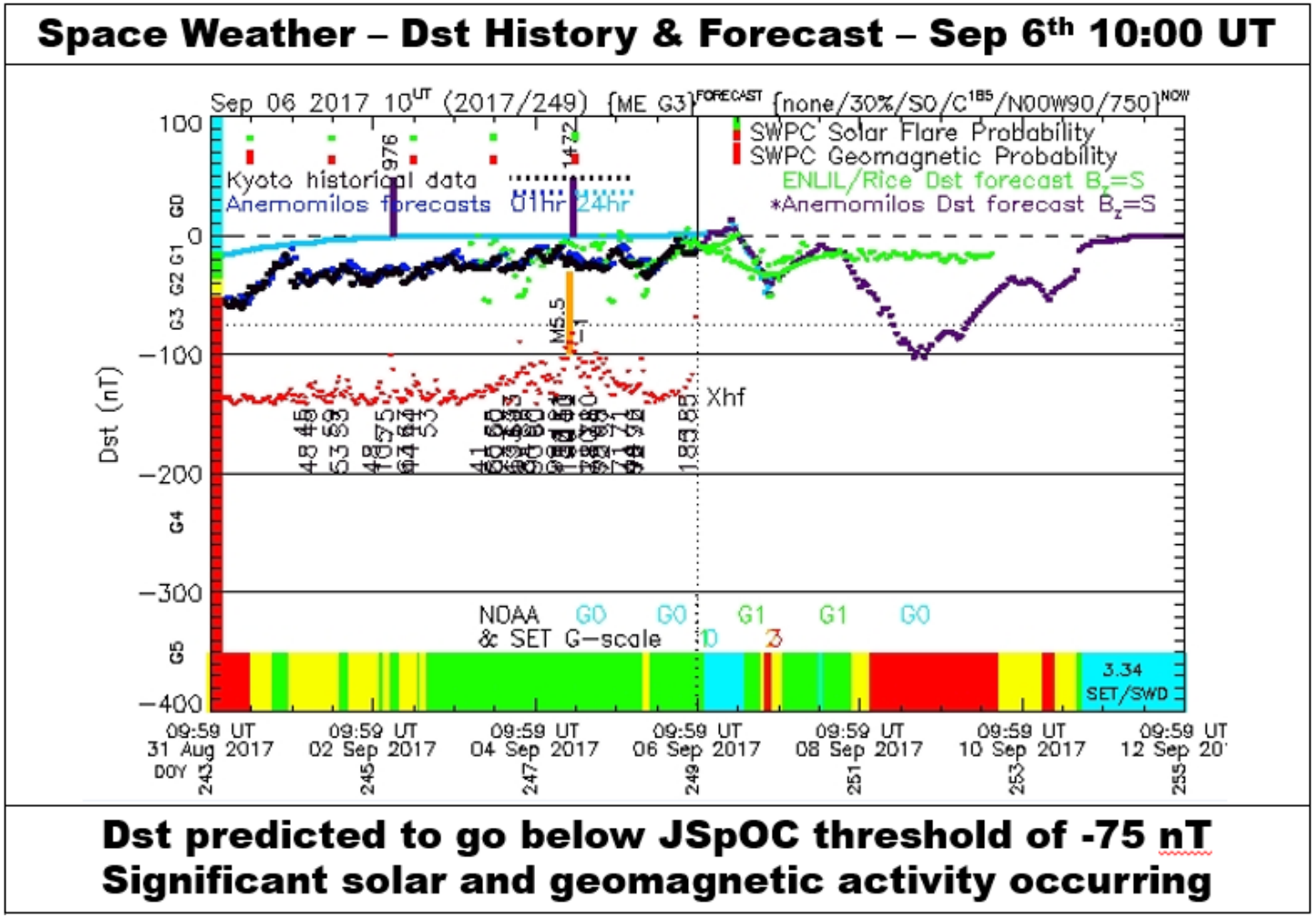


Updated September 6, 2017 at 19:16:12 UTC
NOAA/SWPC Boulder, CO USA

Case Study: Aura vs. 39858

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

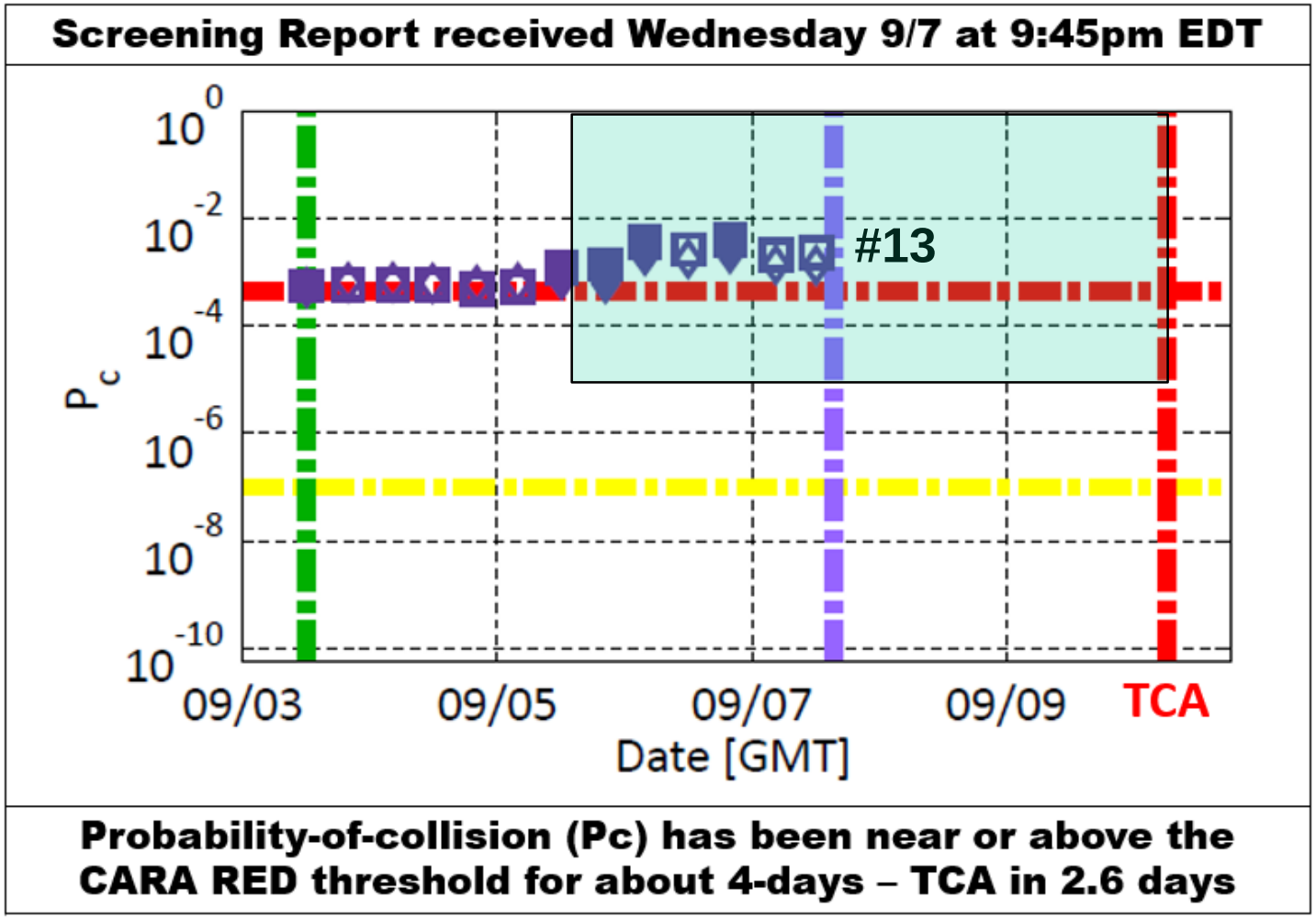
- **September 6th: Dst predicted at storm levels on September 9th**



Case Study: Aura vs. 39858

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

- Sep 7th: 2.6-days until TCA, data point #13, no new tracking, Pc of 1: 743)

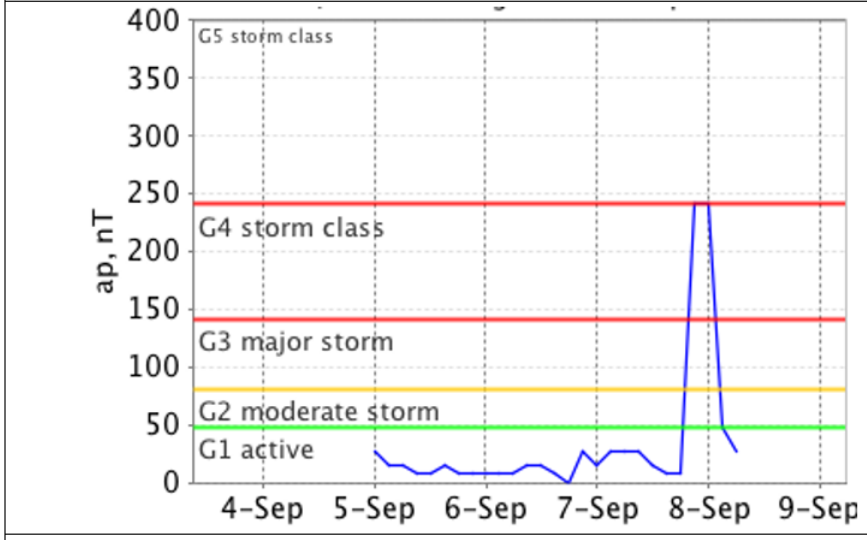


Case Study: Aura vs. 39858

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

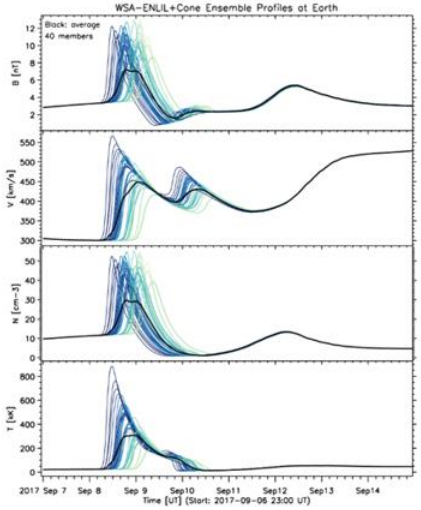
- **September 7th: Geomagnetic Index Ap reached G4 Storm levels on 9/7 as seen from the NOAA/SWPC plot**
- **CME prediction from NASA/GSFC Space Weather Research Center indicates the leading edge of the CME will reach missions near the earth on September 8th**

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



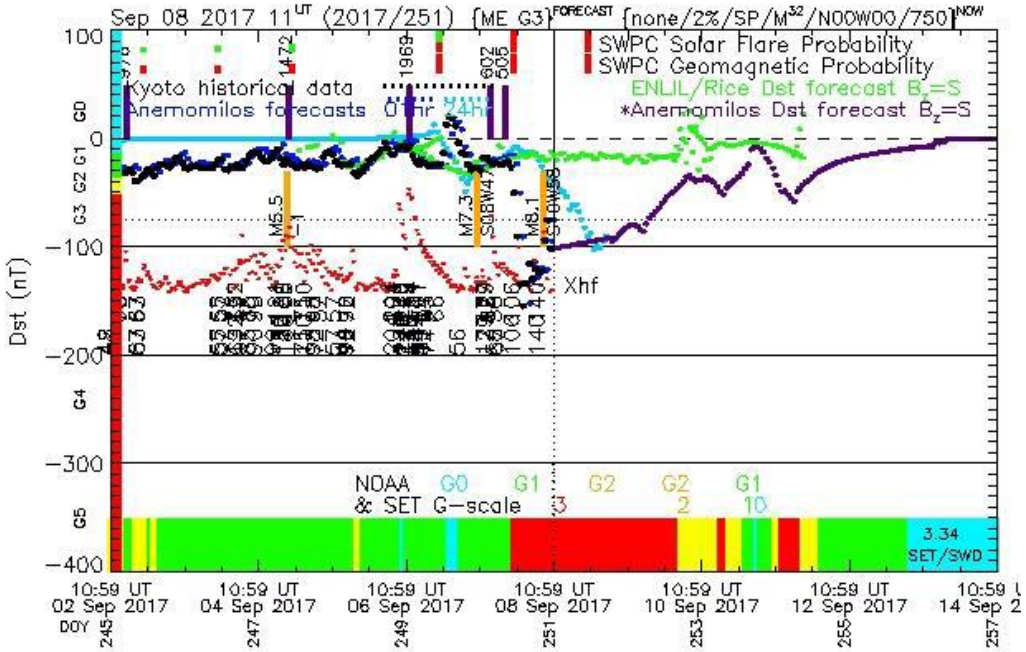
Based on heliospheric ensemble modeling carried out at NASA GSFC Space Weather Research Center, it is estimated that the CME may impact NASA missions near Earth. Out of 40 ensemble members (see notes section), 40 (100%) indicate impact at NASA missions near Earth. Ensemble simulations indicate that the 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).

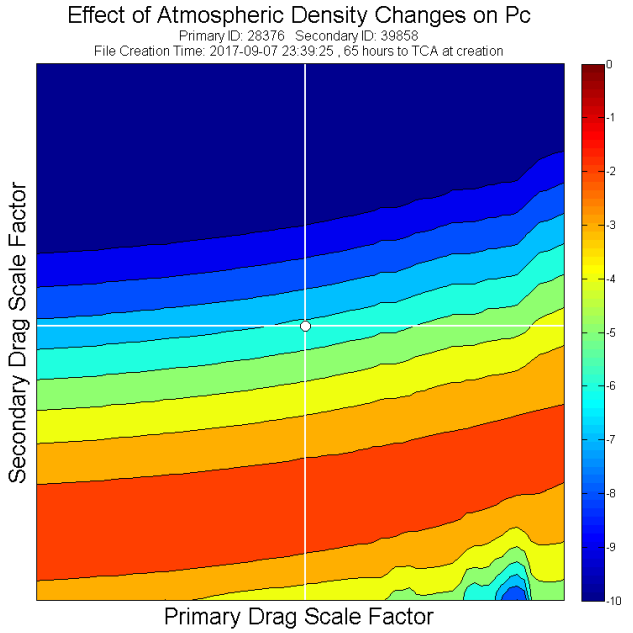
Thursday, September 7th prediction for CME leading edge to reach missions near the earth on September 8th

Case Study: Aura vs. 39858

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

- **September 7th: 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 RIC uncertainties in the in-track and cross-track directions
- **September 8th: CARA Conducts HIE Briefing for the Aura FST**
  - Data point 15 estimated ASW Pc is 1.54E-4 (1 in 6493) – CARA YELLOW
  - Continue to monitor, perform DAM if the estimated Pc increases to RED threshold



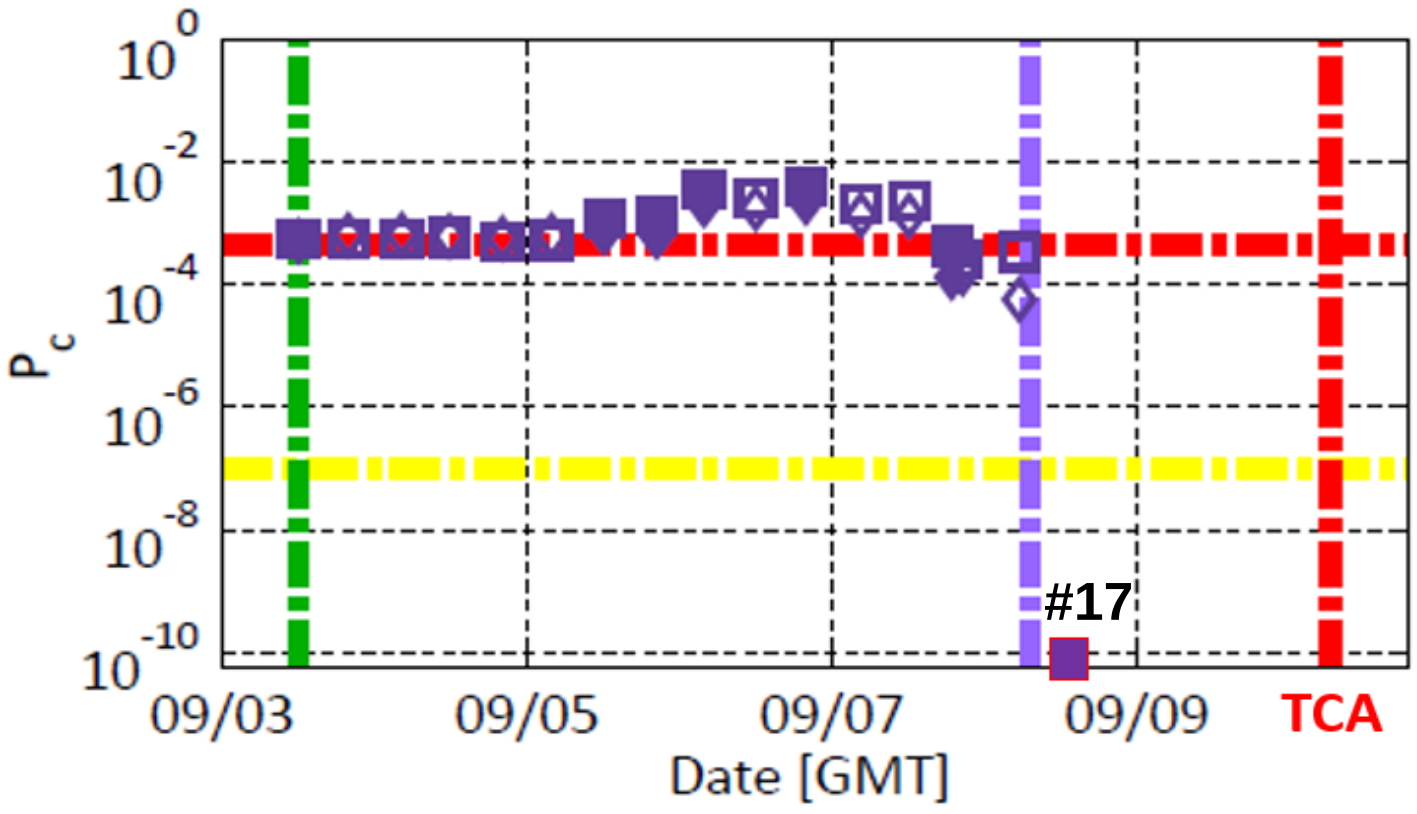


Case Study: Aura vs. 39858

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

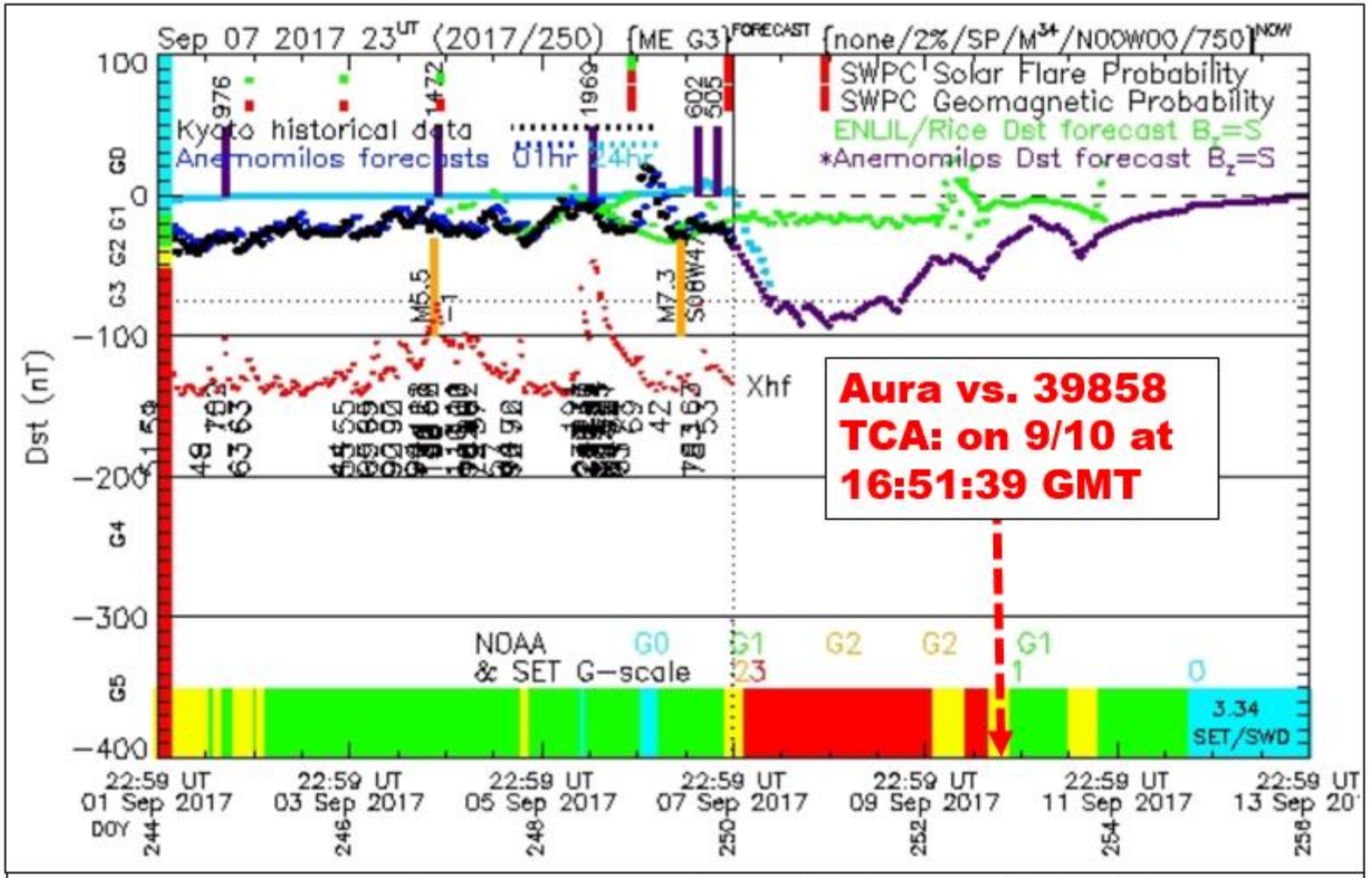
- **1.8-days until TCA (data point #17)**

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



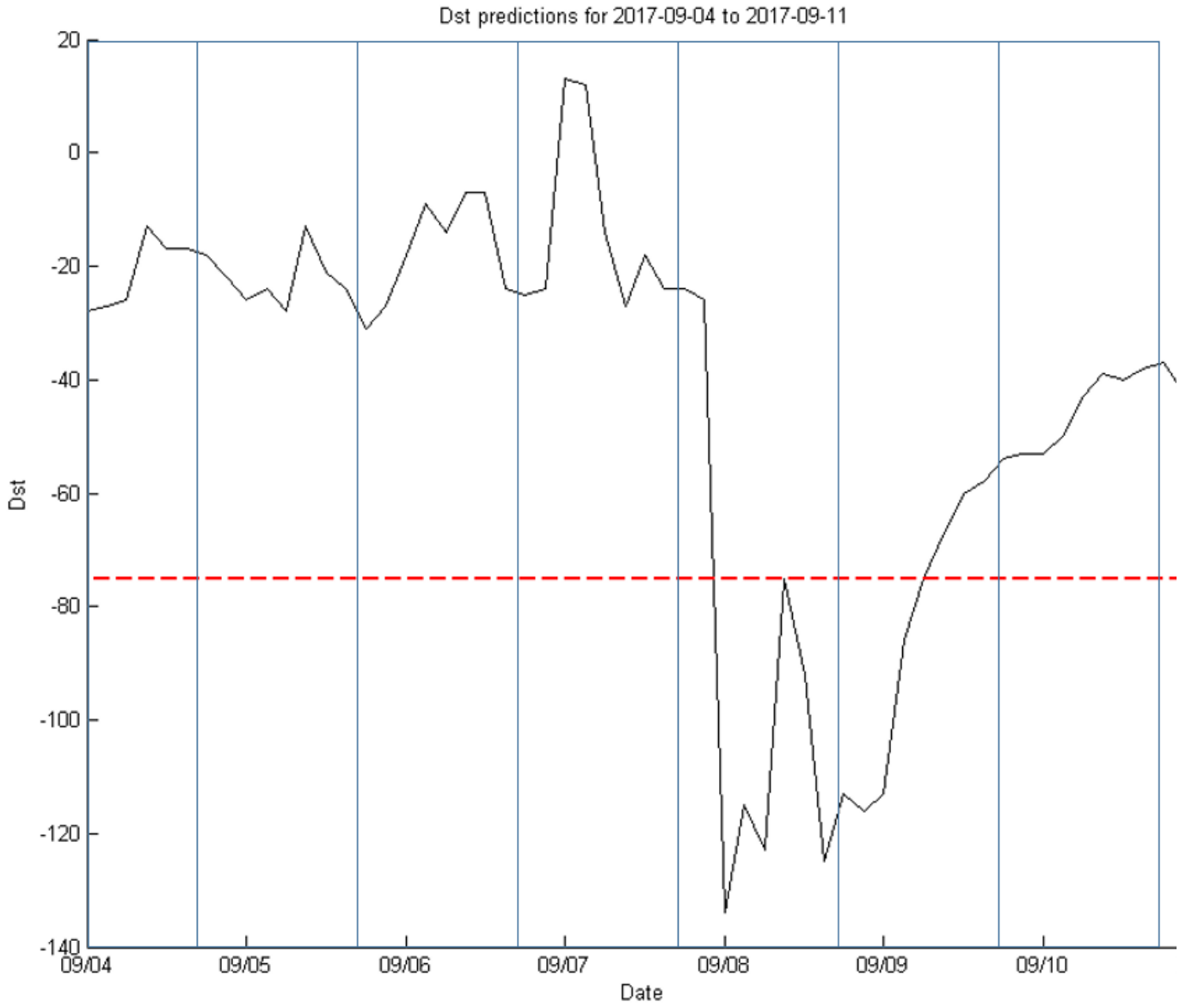
Probability-of-collision (Pc) dropped to zero over the course of the last 3 screening reports and remained at zero

Space Weather – Dst History & Forecast



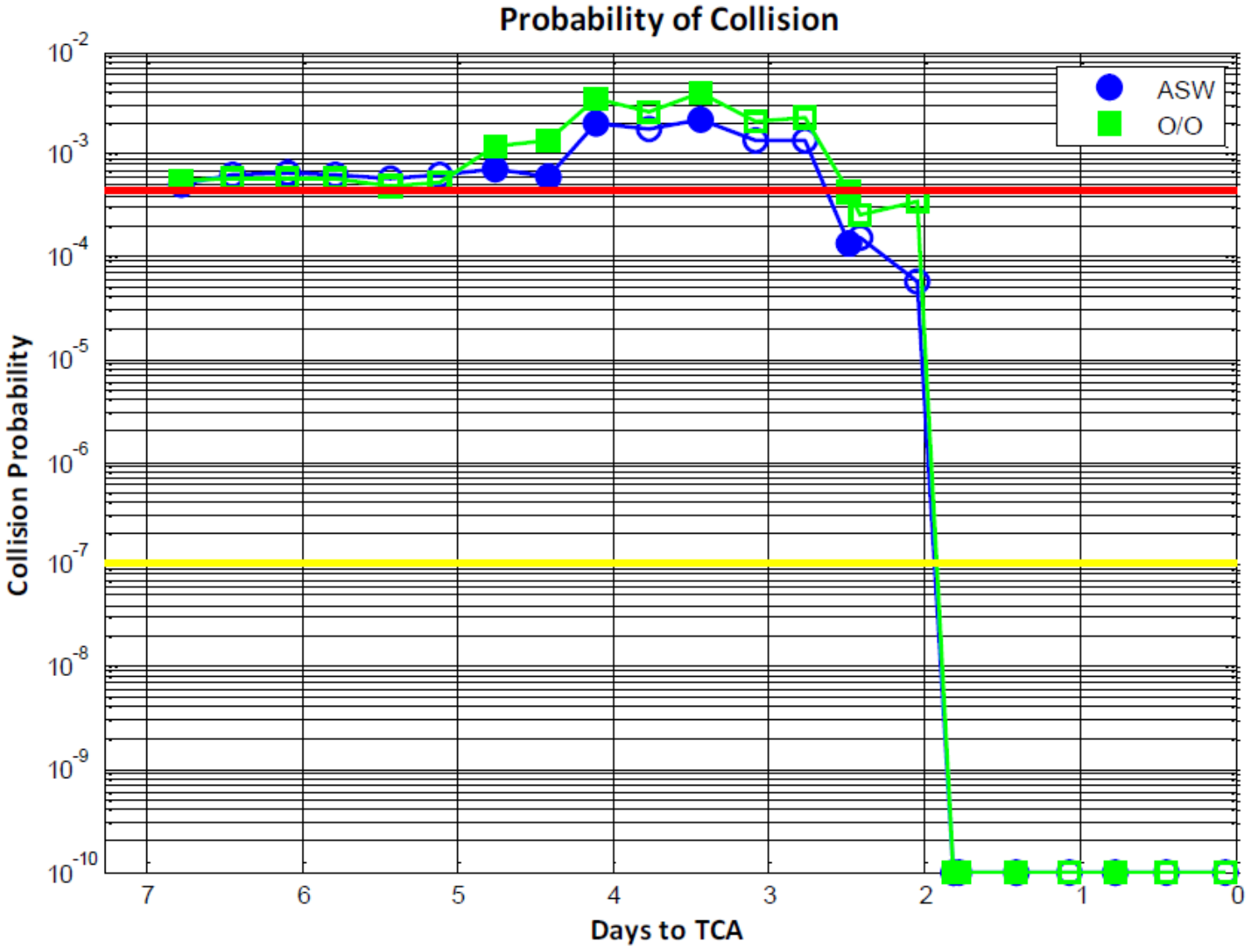
Intense solar and geomagnetic activity predicted to occur prior to the predicted time of close approach (TCA)

Space Weather – Dst History



10/11/2017 9:21 AM

Pc History


Probability of Collision
ASW
O/O
Collision Probability
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
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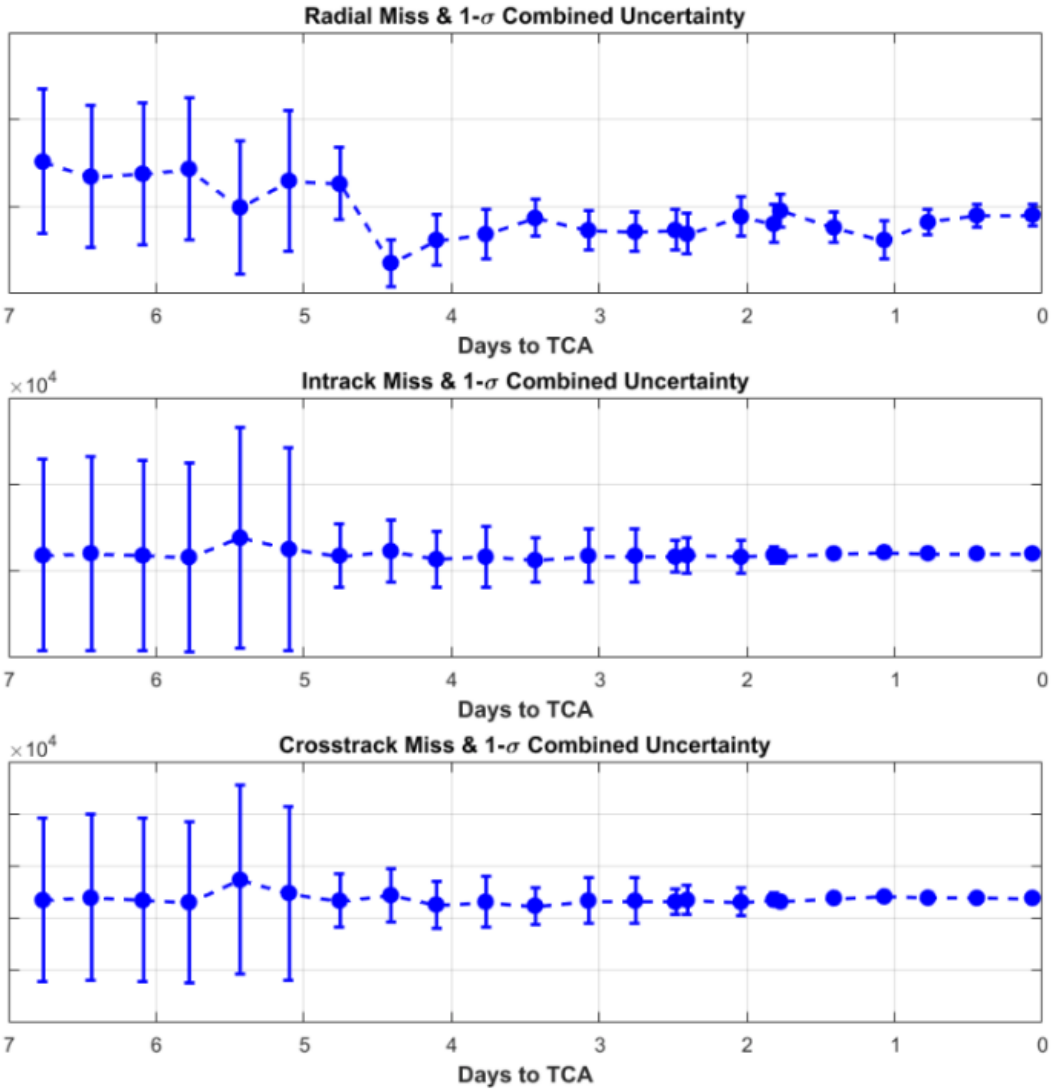
7
6
5
4
3
2
1
0
Days to TCA

Predicted Miss Distances and Uncertainties

Why don't we see changes in the uncertainties?



Aura vs. 39858

(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 28, 2015
- **Bottom Line: We need a better understanding of space weather effects on predicted high-risk conjunctions.**

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

- **Why did the Pc drop off to such a low value just 2 days prior to TCA, after being in the E-03 range for many days, even though the overall miss distance was continuing to decrease?**
- **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?**

Questions

Abbreviations / Acronyms List

ASW –	Astrodynamics Workstation
CA –	Conjunction Assessment
CARA –	Conjunction Assessment Risk Analysis
CRMS –	Collision Risk Management System
DAM –	Debris Avoidance Maneuver
DMUM –	Drag Make-up Maneuver
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)