2023 CNES International Conjunction Assessment Workshop

Recent Earth Observing System (EOS) Aqua Operational Collision Avoidance Experience

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Topics

- **Operational Collision Avoidance (OCA) Background**
- **Aqua Afternoon Constellation (A-Train) Exit Planning**
- **Aqua Passing GCOM-W1 Event**
- **Observations/Lessons Learned**
- **Questions**
- **Backup Slides**
  - Earth Observing System (EOS) – Terra, Aqua and Aura Background
  - International Earth Science Constellation (ESC) Background
  - Aqua Passing GCOM-W1 Details

Background

- **NASA's Earth Science Mission Operations (ESMO) Project's experience with Operational Collision Avoidance (OCA) began in 2002.**
- **ESMO Collision Risk Management (CRM) process has been supported by two systems.**
  - SpaceNav Collision Risk Management System (CRMS)
  - NASA Conjunction Assessment and Risk Analysis (CARA) Team
- **ESMO and CARA worked together to Devolve CARA Conjunction Analysis (CA) operations capabilities into the EOS Control Center. Mission Operations CA (MOCA)**
  - ESMO Pilot Program with CARA – Completed 9/25/2019
    - > CARA continues to provide shadow support if needed
  - EOS transitioned to CRMS (**ESMO MOCA CONOPS**)

Aqua A-Train Exit Planning

Aqua A-Train Exit Plan

History (2020 – 2022) – During COVID Pandemic

- **September 2020 – Virtual MOWG Meeting (VMM) #1**
  - NASA Debris Assessment Software (DAS) Changes and new Solar Flux Models
  - Fuel Usage and Plans for Spring 2021 Inclination Adjust Maneuvers (Aqua's last IAMs)
  - A-Train Constellation Exit Plans – Aqua Flight Operations Team
  - DAS Orbital Decay – Before and After DAS Solar Flux Model Changes
- **May 2021 – VMM #2 – Aqua Constellation Exit Review (CER)**
  - Exit planned for January 2022 (CEMs and PLMs)
  - EOS Flight Dynamics Support (FDS) team Safety Analysis
- **September 28, 2021 (Aqua Mini-MOWG) – Virtual/Teleconference**
  - Science Team Presentation
  - Aqua Orbital Decay Analysis (SpaceNav)
- **November 2021 – VMM #3 – Aqua Delta CER (dCER)**
  - Updated FDS Safety Analysis
  - Proposed Aqua Free-drift, Drag-down A-Train Constellation Exit Approach
- **January 2022: Aqua A-Train Constellation Exit**
- **April 3, 2022: Aqua safely passed GCOM-W1**
- **May 2022 – VMM #4**
  - Aqua/GCOM-W1 Passing Event Executive Summary
  - FDS Free-drift, Drag-down Passing Analysis
- **November 2022 – Virtual/Hybrid Meeting at GSFC**
  - Aqua Passing and Crossing Plans

Aqua/GCOM-W1 Passing Plan Calendar

	Sun	Mon	Tue	Wed	Thu	Fri	Sat
January 2022	January 16	17	18	19 ► GCOM-W1 IAM #21	20 ► OCO-2 IAM #33	21	*22*
	23	24	25	26	27 ► OCO-2 IAM #34	28	29
	30	31	01	02	03 ► OCO-2 IAM #35	04 Distribute Baseline Aqua/GCOM-W1 Passing Plan	05
February 2022	06	07 Aqua/GCOM Kick-Off Telecon #1	08	09 ▲ GCOM-W1 Retro-grade Maneuver	10 ► OCO-2 IAM #36	11 *National Foundation Day (Japan)*	12
	13	14	15	16	17	18 Aqua/GCOM-W1 Passing Plan Feedback due	19
	20	21 *President's Day (US)*	22	23 *Emperor's Birthday (Japan)* ► GCOM-W1 IAM #22	24	25	26
	27	28 Aqua/GCOM Telecon #2	01	02 ► Aura IAM #77	03 GCOM-W1/81668 HIE – Potential RMM	04 GCOM-W1 Tentative DMUM Plan Update Passing Plan	05 Aqua 39874 HIE
March 2022	06 1-Month to Passing GCOM-W1	07 Aqua/GCOM Telecon IF NEEDED	08 GCOM-W1 Fixed DMUM Plan	09 ► Aura IAM #78 ▲ GCOM-W1 Drag Make Up Maneuver	10	11 GCOM-W1 Post DMUM Ephemeris delivery	12
	13 *Daylight saving time starts (U.S.)*	14 Aqua/GCOM Telecon #3	15 GCOM-W1 Ephemeris delivery	16 ► Aura IAM #79	17	18 Distribute updated Aqua/GCOM-W1 Passing Plan	19 GCOM 38132 HIE
	20	21 *Vernal Equinox Day (Japan)*	22 GCOM-W1 Ephemeris Delivery	23	24	25	26
	27	28 Aqua/GCOM-W1 Conjunction Assessment (CA) Data In Daily CA Screening Reports	29 Aqua/GCOM Telecon #4 Aqua/42251 HIE "Not Actionable"	30 GCOM-W1/82932 TCA on 3/31 HIE – Potential RMM	31 Aqua/GCOM Telecon #5 at 8pm	1 Aqua/GCOM Telecon #6 at 8pm	2
April 2022	3 Aqua Passed GCOM-W1	4 Aqua/GCOM-W1 Telecon (Post-Passing) *** Postponed ***	5 Aqua/36012 Low Miss Distance HIE Self-mitigated	6 Aqua/35227 HIE Self-mitigated	7	8 Old Aqua / GCOM-W1 Passing Date (one of many)	9

Aqua/GCOM-W1 Passing Plan Schedule

Date	DOW	Days to Passing	Weeks to Passing	Event
01/19/22	Wed	T-74 days	T-10.5 weeks	GCOM-W1 IAM #21
02/07/22	Mon	T-55 days	T-8.0 weeks	GCOM-W1/Aqua Telecon #1
02/09/22	Wed	T-53 days	T-7.5 weeks	GCOM-W1 Retrograde Maneuver
02/23/22	Wed	T-39 days	T-5.5 weeks	GCOM-W1 IAM #22
03/16/22	Fri	T-37 days	T-5.3 weeks	Aqua/ESMO/SN analysis 1 of Passing Event
02/28/22	Mon	T-34 days	T-5.0 weeks	GCOM-W1/Aqua Telecon #2
03/09/22	Wed	T-31 days	T-3.5 weeks	GCOM-W1 Drag Make Up Maneuver
03/11/22	Fri	T-23 days	T-3.2 weeks	GCOM-W1 delivers Final Predicted Ephemerides
03/14/22	Mon	T-20 days	T-2.9 weeks	GCOM-W1/Aqua Telecon #3
03/16/22	Wed	T-18 days	T-2.5 weeks	Aqua/ESMO/SN analysis 2 of Passing Event
03/18/22	Fri	T-16 days	T-2.3 weeks	ESMO/Aqua decision to use Opportunity #1 (if needed)
03/23/22	Thu	T-11 days	T-1.6 weeks	Opportunity #1 to alter geometry (move along Track)
03/27/22	Sun	T-7 days	T-1.0 weeks	CA Reports include passings
03/29/22	Tue	T-5 days	T-0.7 weeks	GCOM-W1/Aqua Telecon #4
03/31/22	Thu	T-3 days	T-0.4 weeks	Opportunity #2 to alter geometry (Pc based)
04/03/22	Sun	T-0 days	T-0.0 weeks	Aqua Passing CGOM-W1

Aqua vs. GCOM-W1

Orbit Passing Event 4/3/2022

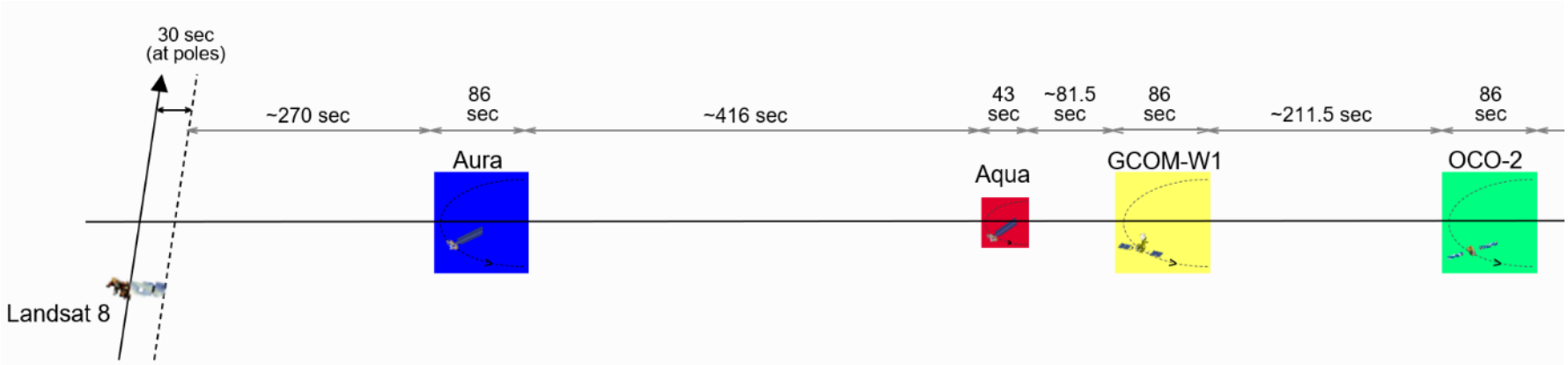


Image Credit: ESMO Constellation Coordination System

Aqua vs. GCOM-W1 Pre-Passing Analysis

The Aqua team performed weekly passing analysis using the latest GCOM-W1 and current Aqua ephemerides, with Aqua being the primary object. Analysis performed on March 23rd showed that the minimum crossing miss distance was expected to be 102-meters with 102-meter radial separation.

GCOM-W1: SOEMP-MAN-LONG.GCOMW1.F20220322.000000.T20220501.000000
Aqua: PM_EOSEPHM7_082_2022_01.e (Predicted STK3 format product rule)

GCOM-W1 vs. Aqua: Pre-Passing Analysis (SpaceNav)

Crossing	TCA (UTC)	Total Miss (m)	Radial (m)	In-Track (m)	Cross-Track (m)
Southern	2022-04-03 at 13:15:58	**932.396**	321.862	875.006	11.478
Northern	2022-04-03 at 14:05:25	**102.133**	102.106	2.345	-0.007

GCOM-W1 vs. Aqua: Pre-Passing Analysis (FDS)

Crossing	TCA (UTC)	Total Miss (m)	Radial (m)	Along-Arc (m)	Cross Track (m)
Southern	2022-04-03 at 13:15:58	**932.41**	321.92	875.02	7.27
Northern	2022-04-03 at 14:05:25	**102.200**	102.11	2.37	3.59

Aqua vs. GCOM-W1 Probability of Collision (Pc)

The Probability of collision (Pc) is the principal metric used to specify the risk of collision between the primary object (our satellite) colliding with the secondary object of concern. In the image below, Pc thresholds are defined and classified by color for EOS missions to specify what course of action is taken for which Pc range.

	Pc Thresholds	Odds Range	Course of Action	Sample Scenarios
Yellow	**($1.0e^{-4}$-$1.0e^{-5}$)**	1:10,000 to 1:100,000	**No DAM**	
Orange	**($1.0e^{-3}$-$1.0e^{-4}$)**	1:1,000 to 1:10,000	**DAM**	Execute maneuver or request waiver if burn size is too large and data has too much uncertainty
Red	**($1.0e^{-2}$-$1.0e^{-3}$)**	1:100 to 1:1,000	**DAM**	Execute maneuver
Black	**≥$1.0e^{-2}$**	1:1 to 1:100	**DAM**	**Maneuver at all costs** Even if Ongoing Anomaly (Non-Maneuver Component)

Aqua vs. GCOM-W1 (ASW vs. ASW)

We begin to receive screening data from within 7 days of the Time of Closest Approach (TCA) for any event . The data assessed this far out is more for situational awareness. The predicted data for the passing event date was expected in our Collision Risk Management System (CRMS) Summary Reports.

Report Gen Time to TCA [Days]	Screening Epoch	TCA [UTC]	Collision Probability	Total Miss [m]	Radial Miss (Uncertainty) [m]	In-Track Miss (Uncertainty) [m]	Cross-Track Miss (Uncertainty) [m]
6.7	2022-03-27 14:09:49	2022-04-03 09:08:45	1.72e-04 1:5814	825	68 (27.3)	823 (3219.0)	-7 (33.9)
6.4	2022-03-27 22:14:43	2022-04-03 09:08:45	4.92e-07 1:2M	767	114 (26.4)	759 (3132.2)	-7 (33.7)
6.1	2022-03-28 06:10:33	2022-04-03 09:08:45	1.29e-07 1:8M	194	131 (27.9)	143 (2952.7)	-1 (31.8)
5.7	2022-03-28 14:27:47	2022-04-03 09:08:45	8.07e-08 1:12M	382	127 (25.6)	360 (2244.8)	-3 (24.9)
5.4	2022-03-28 22:05:29	2022-04-03 09:08:45	6.02e-09 1:166M	260	145 (26.4)	216 (2273.3)	-2 (25.3)
5.0	2022-03-29 07:08:22	2022-04-03 09:08:45	7.43e-09 1:135M	435	152 (27.7)	-407 (2286.0)	4 (25.6)

Aqua vs. GCOM-W1 (ASW vs. ASW)

Our automated maneuver planning begins within 3 days to TCA for yellow or higher risk events. For this event, our risk level went up to orange right before the 3-day mark, so we were prepared to begin maneuver planning with the intent to maneuver if the risk didn't subside.

Report Gen Time to TCA [Days]	Screening Epoch	TCA [UTC]	Collision Probability	Total Miss [m]	Radial Miss (Uncertainty) [m]	In-Track Miss (Uncertainty) [m]	Cross-Track Miss (Uncertainty) [m]
4.7	2022-03-29 14:04:43	2022-04-03 09:08:45	2.47e-05 1:40K	100	100 (28.6)	-10 (1920.6)	0 (22.4)
4.4	2022-03-29 22:12:36	2022-04-03 09:08:45	1.57e-06 1:636K	374	106 (24.1)	-358 (1883.6)	3 (22.3)
4.0	2022-03-30 07:09:14	2022-04-03 09:08:44	3.71e-06 1:269K	990	96 (24.7)	-986 (2961.1)	9 (31.8)
3.7	2022-03-30 14:04:07	2022-04-03 09:08:44	1.77e-05 1:56K	899	81 (22.6)	-896 (2667.2)	8 (29.0)
3/30: X-Class Solar Flare (X1.38) with peak at 17:37 GMT							
3.4	2022-03-30 22:13:05	2022-04-03 09:08:44	1.31e-04 1:7634	1004	64 (21.2)	-1002 (2524.5)	8 (27.3)
3.1	2022-03-31 05:57:37	2022-04-03 09:08:44	8.41e-04 1:1189	1040	45 (19.7)	-1039 (2322.3)	8 (25.2)

Aqua vs. GCOM-W1 (ASW vs. ASW)

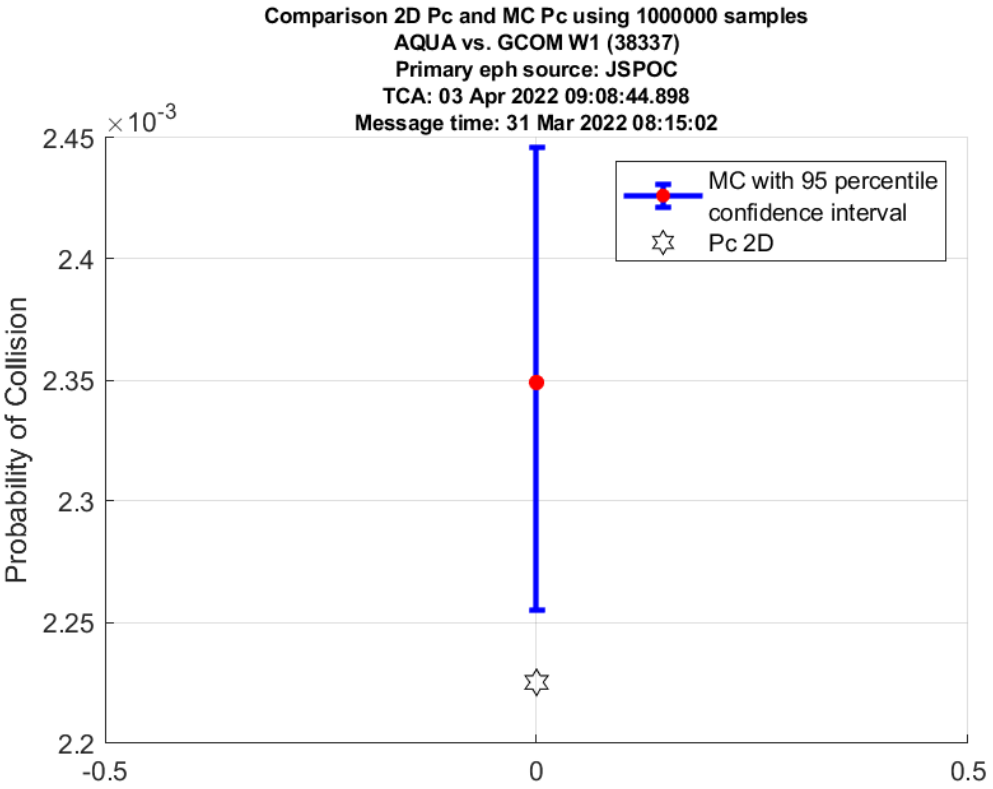
CRMS began generating Risk Mitigation Maneuver options with the update 2.9 days to TCA, which now turned red with a low radial miss distance. A Monte Carlo simulation was also run by SpaceNav to confirm agreement with the updated red Pc for this passing.

Report Gen Time to TCA [Days]	Screening Epoch	TCA [UTC]	Collision Probability	Total Miss [m]	Radial Miss (Uncertainty) [m]	In-Track Miss (Uncertainty) [m]	Cross-Track Miss (Uncertainty) [m]
2.9	2022-03-31 08:15:02	2022-04-03 09:08:44	2.23e-03 1:448	938	34 (18.6)	-938 (2056.1)	7 (22.8)
2.7	2022-03-31 14:26:14	2022-04-03 09:08:44	2.67e-03 1:375	1087	33 (17.6)	-1087 (1764.0)	8 (20.1)
3/31 at 17:59:08 GMT Aqua entered Safe Mode (Unable to maneuver) ~ First time since 2002							
2.4	2022-03-31 22:03:35	2022-04-03 09:08:44	3.23e-03 1:310	1023	33 (17.5)	-1022 (1431.9)	8 (17.2)
2.1	2022-04-01 02:23:43	2022-04-03 09:08:44	2.05e-03 1:488	871	39 (17.1)	-870 (1367.9)	7 (17.4)
2.1	2022-04-01 03:11:12	2022-04-03 09:08:44	1.44e-03 1:694	849	43 (16.7)	-848 (1216.6)	7 (15.4)
2.1	2022-04-01 03:43:36	2022-04-03 09:08:44	1.53e-03 1:654	834	43 (16.6)	-833 (1212.9)	6 (15.3)

Aqua went into Safe Mode while the risk for the event was red. Due to a loss of maneuver capability, and the need to maneuver based off the Pc, the Aqua team reached out and informed the GCOM-W1 team of the situation. The GCOM-W1 team agreed that they will maneuver if necessary.

Aqua vs. GCOM-W1 Monte Carlo Analysis

This event had a relative velocity of 127 m/s. A Monte Carlo is run as part of our process for high-risk low relative velocity events



The Monte Carlo Pc of 2.35e-03 matched very closely with the 2D Pc of 2.23e-03

Report Gen Time to TCA [Days]	Screening Epoch	TCA [UTC]	Collision Probability	Total Miss [m]	Radial Miss (Uncertainty) [m]	In-Track Miss (Uncertainty) [m]	Cross-Track Miss (Uncertainty) [m]
2.9	2022-03-31 08:15:02	2022-04-03 09:08:44	2.23e-03 1:448	938	34 (18.6)	-938 (2056.1)	7 (22.8)

Image Credit: SpaceNav Collision Risk Management System

Aqua vs. GCOM-W1 (ASW vs. ASW)

About 1.4 days from the predicted TCA the Pc dropped below the CRMS maneuver planning threshold of 1.0e-05, with an increase in radial miss distance.

Aqua remained in Safe Mode throughout this period below.

Report Gen Time to TCA [Days]	Screening Epoch	TCA [UTC]	Collision Probability	Total Miss [m]	Radial Miss (Uncertainty) [m]	In-Track Miss (Uncertainty) [m]	Cross-Track Miss (Uncertainty) [m]
1.9	2022-04-01 06:07:48	2022-04-03 09:08:45	2.36e-03 1:424	608	42 (15.7)	-606 (734.0)	5 (11.7)
1.9	2022-04-01 07:40:53	2022-04-03 09:08:45	2.36e-03 1:424	608	42 (15.7)	-606 (734.0)	5 (11.7)
1.7	2022-04-01 14:25:20	2022-04-03 09:08:44	2.42e-03 1:413	842	37 (14.8)	-841 (579.9)	6 (10.8)
1.4	2022-04-01 22:09:09	2022-04-03 09:08:44	4.08e-07 1:2M	1071	76 (13.7)	-1068 (433.9)	9 (10.4)
1.3	2022-04-02 00:13:15	2022-04-03 09:08:44	6.31e-08 1:16M	1051	80 (13.1)	-1048 (376.5)	9 (10.4)
1.2	2022-04-02 02:36:31	2022-04-03 09:08:44	6.32e-08 1:16M	1078	79 (12.9)	-1075 (364.1)	9 (10.3)
1.2	2022-04-02 04:11:41	2022-04-03 09:08:44	2.12e-08 1:47M	1048	78 (12.9)	-1045 (273.2)	9 (10.1)
1.1	2022-04-02 06:04:44	2022-04-03 09:08:45	5.91e-09 1:169M	1011	78 (12.8)	-1008 (236.2)	8 (10.0)

Aqua vs. GCOM-W1 (ASW vs. ASW)

The day of the predicted passing event the Pc continued to drop and Aqua uneventfully passed GCOM-W1 with neither mission required to take any evasive action. Aqua went back into normal operating mode and regained maneuver capability ~8.5 hours before TCA.

Report Gen Time to TCA [Days]	Screening Epoch	TCA [UTC]	Collision Probability	Total Miss [m]	Radial Miss (Uncertainty) [m]	In-Track Miss (Uncertainty) [m]	Cross-Track Miss (Uncertainty) [m]
0.7	2022-04-02 14:26:30	2022-04-03 09:08:44	6.60e-14 1:15T	997	50 (11.5)	-996 (141.0)	8 (9.5)
0.5	2022-04-02 20:52:14	2022-04-03 09:08:44	4.70e-33	968	54 (10.5)	-966 (82.4)	8 (9.2)
0.4	2022-04-02 21:58:56	2022-04-03 09:08:44	6.13e-42	954	53 (10.5)	-953 (71.7)	8 (9.1)
Aqua regained Maneuver capability around 2200 UTC on 4/2							
0.1	2022-04-03 06:34:51	2022-04-03 09:08:45	0.00e+00	997	49 (10.3)	-996 (54.8)	8 (9.2)
Post-Event Data							
Post-Event CDM	2022-04-04 12:02:29	2022-04-03 09:08:44.933	0.00e+00	1028	73.2	-1025.9	9.0

The post event Conjunction Data Message showed that the total miss distance between the two satellites was about 1 kilometer, with a 73-meter radial miss distance.

Aqua vs. GCOM-W1 Post-Passing Analysis

The EOS Aqua Flight Dynamics Support (FDS) team performed a post-event analysis using the latest GCOM-W1 and Aqua definitive ephemerides.

The analysis was performed with Aqua as the primary object and the following passing information was found:

GCOM-W1: SOEMP-DEF_GCOMW1_F20220327_000000_T20220404_000000
Aqua: PM_EOSEPHM7_097_2022_01.e (Predicted STK3 format product rule)

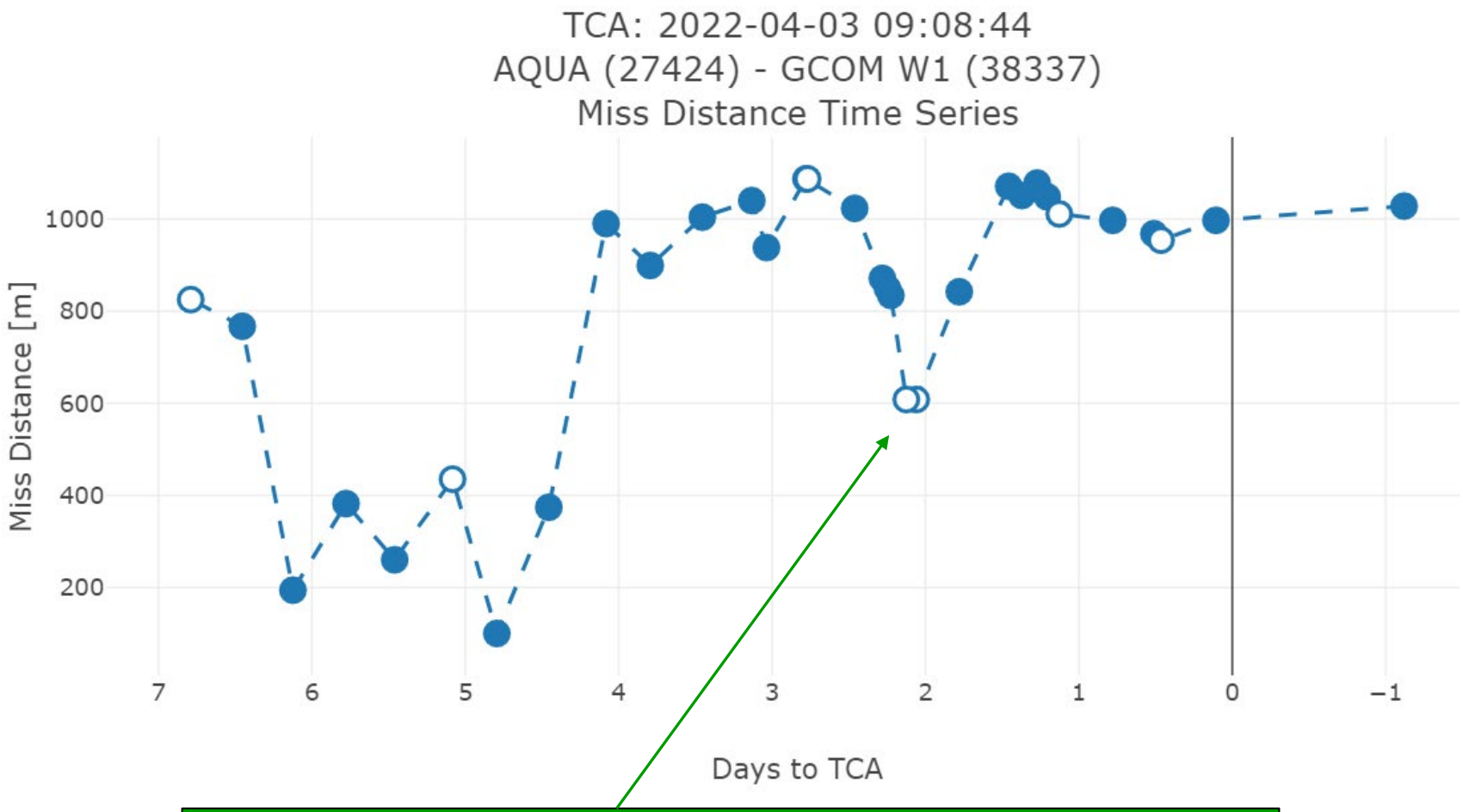
GCOM-W1 vs. Aqua: Post-Passing Analysis (FDS)

Crossing	TCA (UTC)	Total Miss (m)	Radial (m)	Along-Arc (m)	Cross Track (m)
Southern	Apr 03 08:19:18.0	**347.59**	333.27	-98.61	-5.17
Northern	Apr 03 09:08:44.8	**974.18**	104.22	-968.55	8.00

Reference Data from FDS Pre-Passing Analysis

Southern	Apr 03 13:15:58.1	**932.41**	321.92	875.02	7.27
Northern	Apr 03 14:05:24.7	**102.200**	102.11	2.37	3.59

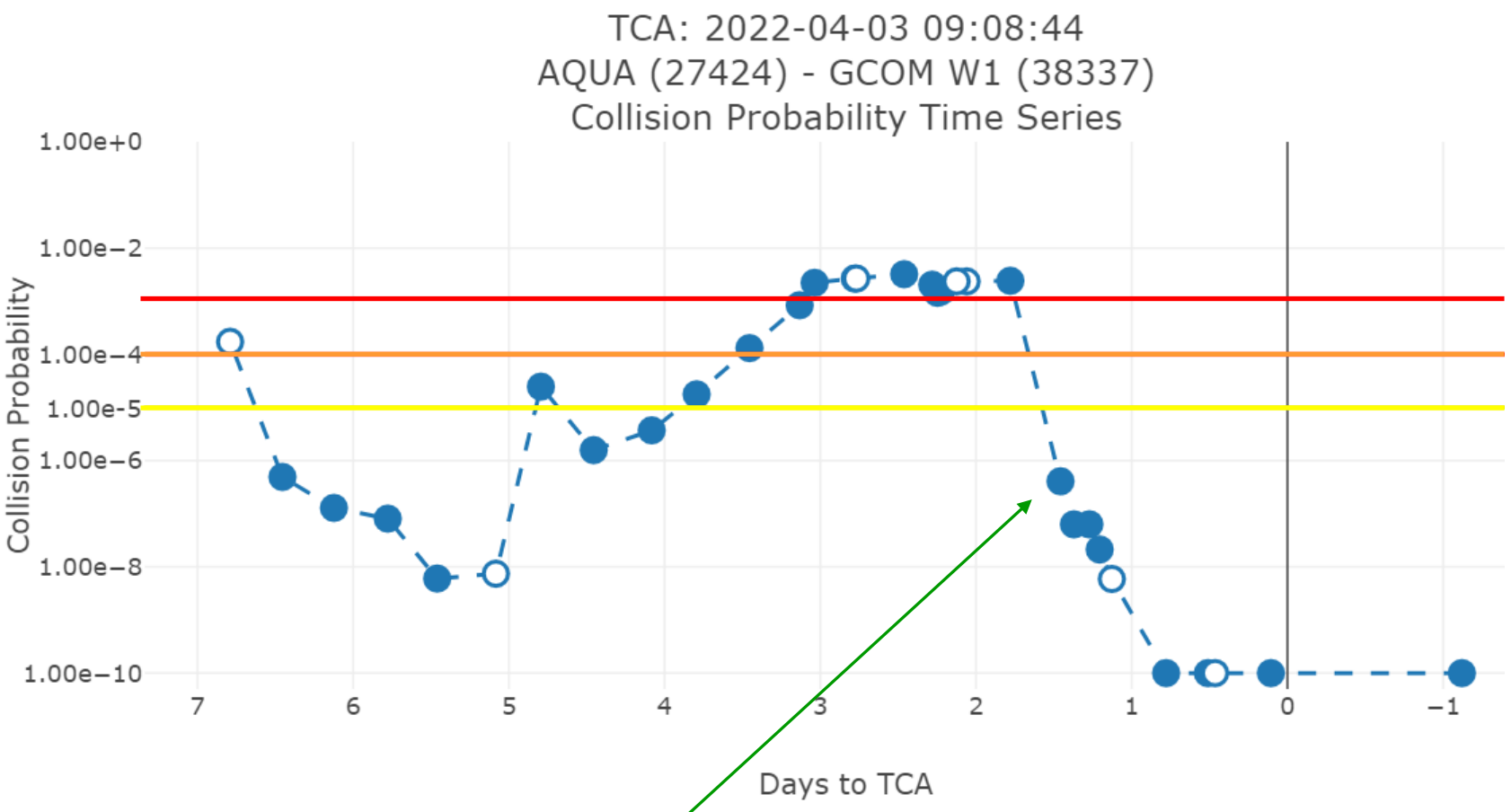
Aqua vs. GCOM-W1
0908 UTC Event Miss Distance



The total miss distance dropped lower without a new track, possibly due to atmospheric changes caused by the solar flare

Image Credit: SpaceNav Collision Risk Management System

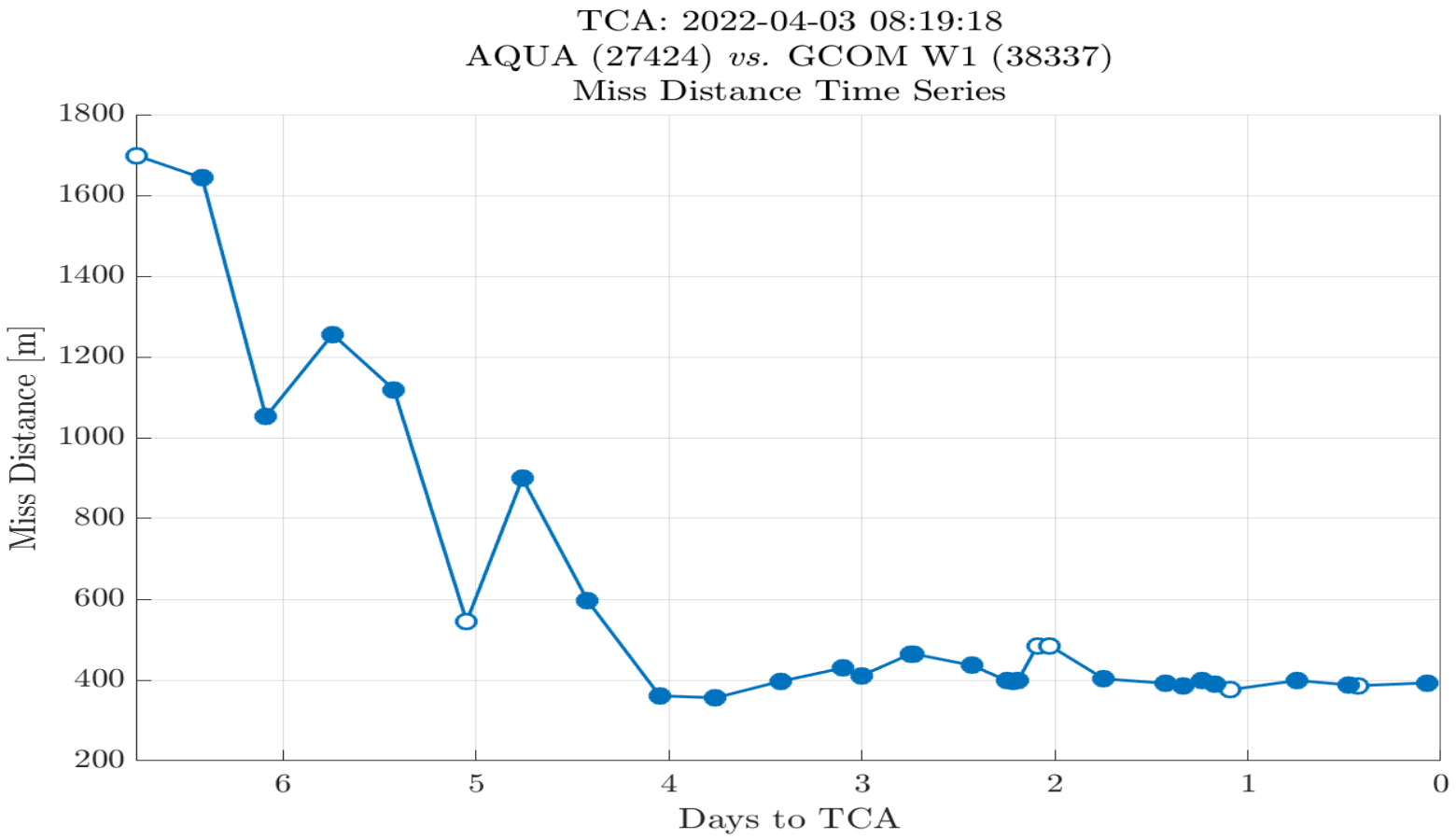
Aqua vs. GCOM-W1 0908 UTC Event Pc



The Pc dropped and continued to drop with updated tracks after the miss distance dropped and went back up

Image Credit: SpaceNav Collision Risk Management System

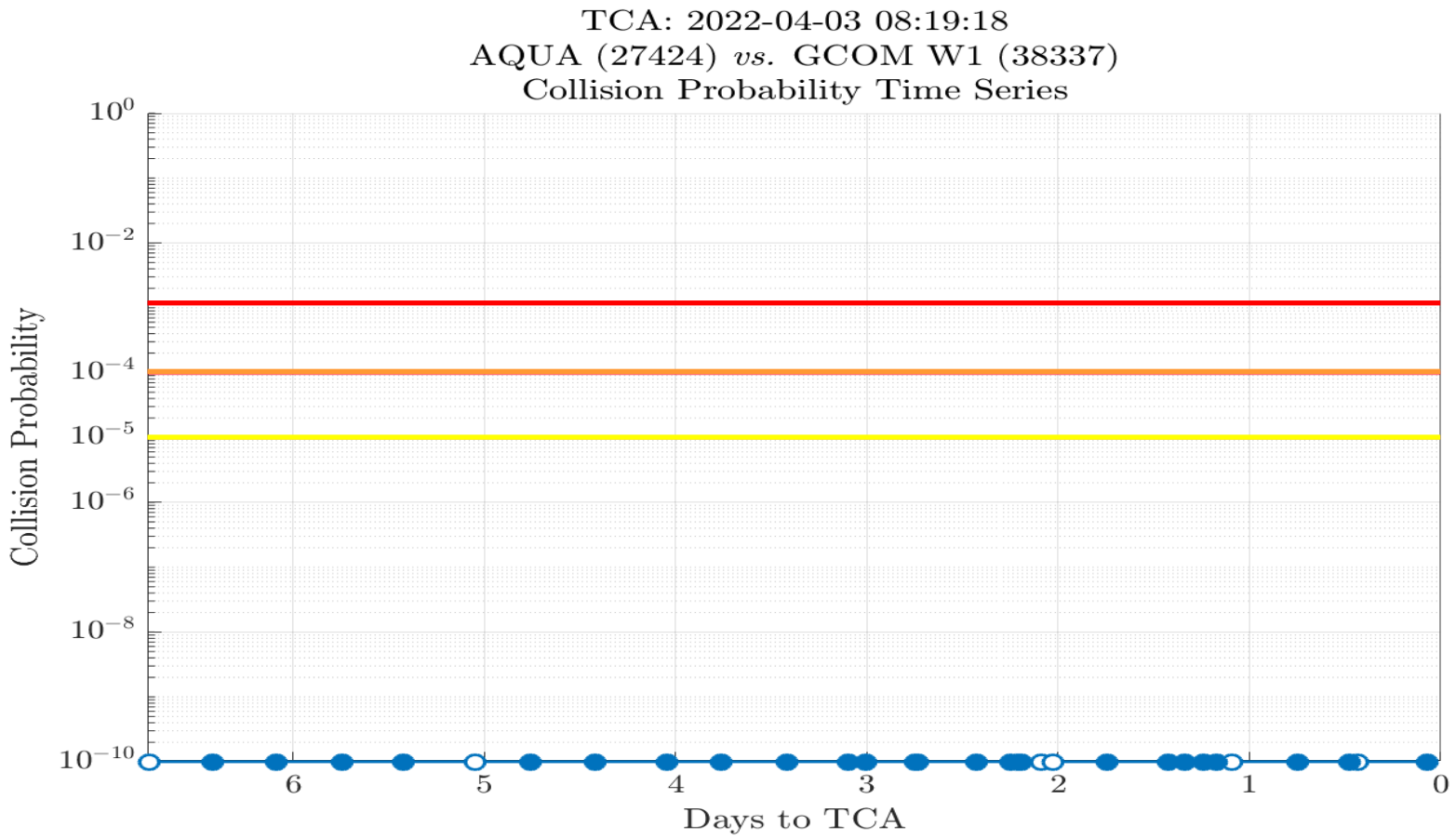
Aqua vs. GCOM-W1
0819 UTC Event Miss Distance



Total miss distance dropped and stayed steady as the event approached TCA but never got below ~350 meters

Image Credit: SpaceNav Collision Risk Management System

Aqua vs. GCOM-W1 0819 UTC Event Pc



The Pc remained negligible for this event throughout the 7-day period

Image Credit: SpaceNav Collision Risk Management System

Aqua/GCOM-W1 Passing Summary

- **Aqua team worked closely with GCOM-W1 team, prior to and during the passing event.**
- **Aqua was predicted to pass GCOM-W1 on April 3, 2022.**
- **Aqua team actively monitored multiple close approach events.**
- **The predicted close approaches were 1315z and 1405z, however they ended up being on 0819z and 0908z.**
- **The northern hemisphere close approach had a larger overall miss distance than the southern, unlike predicted.**
- **Timing and miss distances of the maximum Pc close approach passing event potentially complicated by changes in atmospheric drag (X-Class Solar Flare and Cannibal CME).**
- **Aqua entered Safe Mode on 3/31 at 17:59:08 UTC.**
  - Maneuver capability recovery was not expected before the 4/3 passing event
  - 3/31: ESMO recommended GCOM-W1 begin RMM planning
  - 4/1: By late in the GMT day, it appeared risk level was dropping
  - 4/2: Aqua recovered maneuver capability 6pm local
  - 4/3: At 09:08:44 UTC Aqua safely flew under GCOM-W1

Cannibal CME Reference: https://svs.gsfc.nasa.gov/20067

Observations

- **Every passing/crossing event is unique.**
- **Despite multiple passing/crossing events experienced by the International ESC Morning Constellation (MC) & A-Train missions.**
  - 2011: Landsat-5 and SAC-C crossings with the A-Train
  - 2021: Landsat-7 crossings with the MC and the A-Train
- **Aqua passing GCOM-W1 event experienced significant complicating factors.**
  - General nature of the passing event
    - > Near co-planar (1.0 degrees), low relative velocity (127 m/s)
    - > Multiple monitor volume violations
  - Significant X-Class Solar Flare (X1.38) on 3/30 at 17:37 GMT
  - Aqua Safe Mode on 3/31 at 17:59:08 GMT
- **Despite the multiple challenges it was successfully managed by the multiple teams involved – Thank You.**

Lessons Learned

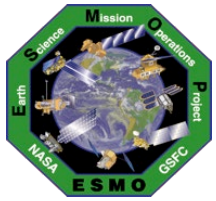
- **Identify stakeholders early and include all parties in passing event communications.**
- **Communicate early and often - Frequent communication is essential especially when the crossing/passing date changes with high frequency (due to other maneuvers or space weather).**
- **Written communication preferred unless short turn-around necessitates verbal (meeting/phone) conversation.**
- **Establish some common ground for delivery/exchange of ephemeris, miss distances information.**

Source 2010 USAF Television Commercial

Abbreviations/Acronyms List

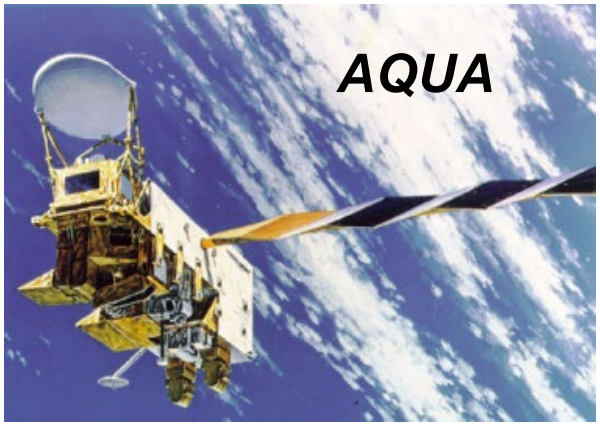
ASW – Astrodynamics Workstation
CA – Close Approach
CA – Collision Avoidance
CA – Conjunction Assessment
CAE – FOT Collision Avoidance Engineer
CAM – Command Authorization Meeting
CARA – Conjunction Assessment Risk Analysis
CALIPSO – Cloud-Aerosol LIDAR and Infrared Pathfinder Satellite Observations
CEM – Constellation Exit Maneuver
CRMS – Collision Risk Management System
DAM – Debris Avoidance Maneuver
DMUM – Drag Make-up Maneuver
EO-1 – Earth Explorer-1
EOS – Earth Observing System
ESC – Earth Science Constellation
ESMO – Earth Science Mission Operations
FDS – Flight Dynamics System
FOT – Flight Operations Team
GCOM-W1 – Global Change Observation Mission for Water (1)
GMT – Greenwich Mean Time
GSFC – Goddard Space Flight Center
HIE – High Interest Event
HQ – Headquarters
JPL – Jet Propulsion Lab
km – kilometer
LaRC – Langley Research Center
m – meter
m/s – Meters/second
MLT – Mean Local Time
MOCA – Mission Operations CA
NASA – National Aeronautics & Space Administration
OCO – Orbiting Carbon Observatory
OCO-2 – Orbiting Carbon Observatory-2
PARASOL – Polarization & Anisotropy of Reflectances for Atmospheric Sciences coupled with Observations from a Lidar
Pc – Probability of Collision
PLM – Perigee Lowering Maneuver
RIC – Radial, In-track, Cross-Track
RMM – Risk Mitigation Maneuver
s or sec – second
SAC-C – Satelite de Aplicaciones Cientificas-C
TBD – To Be Determined
TCA – Time of Closest Approach
USAF – United States Air Force
UTC – Coordinated Universal Time

Backup Slides



EOS/ESC Background

NASA's Earth Observing System (EOS)



As of 3/31/2023	Terra	Aqua	Aura
Launch Date	12/18/1999	5/4/2002	7/15/2004
Current Orbit #	123,840	111,199	99,506
Duration	23y 3m 13d	20y 10m 27d	18y 8m 16d
HIEs (3/31/2023)	277	362	353
DAMs (3/31/2023)	24 (7/29/2022)	13 (11/10/2022)	16 (5/2/2021)

Combined 63+ years of orbital debris collision-free safe operations

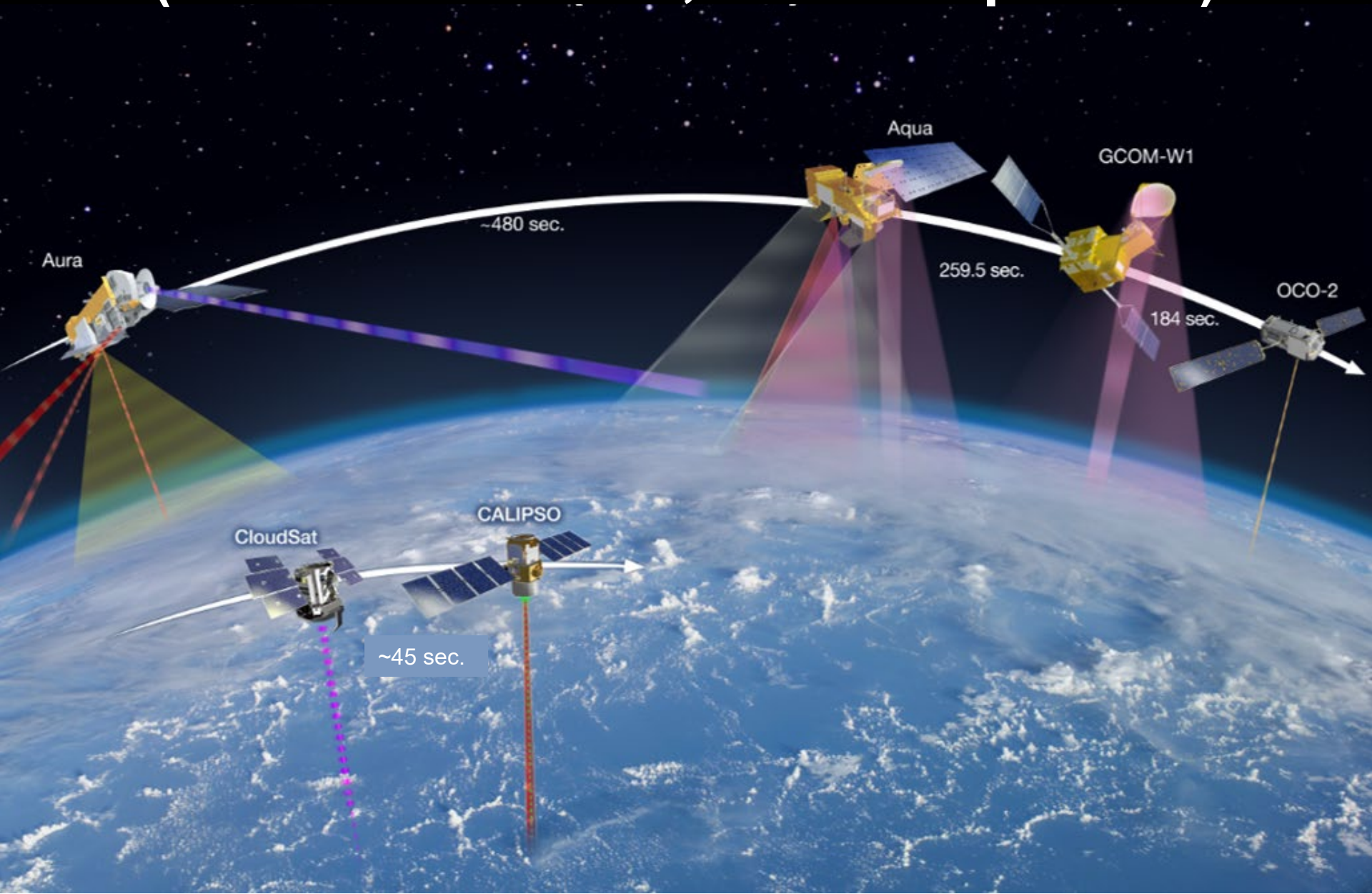
Spacecraft Design/Constraints

- Routinely maneuver to maintain exact repeat orbit/ground track
- Spacecraft designed to perform Drag Make-Up Maneuvers (DMUMs) and Inclination Adjust Maneuvers (IAMs)
  - Retrograde capability not part of nominal maneuver set
- Drag Make-Up Maneuvers therefore used as Debris Avoidance Maneuvers (DAMs) to mitigate collision risk
  - Orbit Raise Maneuver (can only go up, no brake pedal)
- Differences in DMUM and DAM concepts are significant

	DMUMs	DAMs
Purpose	Maintain Orbit Altitude	Avoid Debris
Notification Time	Several Weeks	Few Days or Less
Operations Mentality	Routine, Methodical	Urgent, Quick Turnaround
Contingency Action	Reschedule	Health & Safety Concern
Burn Duration	Well Defined	Variable
Burn Options	One	Multiple
Execution Time	Day Shift Only, M-F	Anytime, Any Day

International Earth Science Constellations (Before Aqua A-Train Exit in January 2022)

Afternoon Constellation (A-Train)
(Late-2018 → 2021, before Aqua Exit)



ESC Constellation History
(March 2023)

- **A-Train Mission Operations Working Group (MOWG):** Exploratory discussions between LaRC, JPL and GSFC in 2001 - 2002. Officially met for the first time in March 2003 at GSFC
- **Morning Constellation:** Officially began with Landsat 7 (April 1999) and Terra (December 1999), followed by joint EO-1/SAC-C (November 2000)
- **Afternoon Constellation (A-Train):** Began with the Aqua (May 2002) and Aura (July 2004), then PARASOL (December 2004), and joint CALIPSO/CloudSat launch (April 2006)
- **Later ESC missions followed:**
  - **OCO** (2010) and **Glory** (2011) launches failed
  - **GCOM-W1** (May 2012), **Landsat 8** (February 2013), **OCO-2** (July 2014), **Landsat 9** (September 2021) successfully reached orbit
- **Formation of the C-Train:**
  - **CloudSat** exited A-Train on February 22, 2018
  - **CALIPSO** exited A-Train in mid-September 2018
  - **C-Train** operational orbit configuration achieved on November 1, 2018
- **Recent Constellation Exits:**
  - January 2022: Aqua began free-drift, drag down A-Train Constellation Exit
  - October 2022: Terra executed Constellation Exit Maneuvers
  - March 2023: Aura began free-drift, drag-down A-Train Constellation Exit

Aqua A-Train Exit Planning Background

Aqua A-Train Exit Plan

History (2007 – 2014)

KEY: YYYY-mm was an ESC MOWG Meeting

- **2007-10: PARASOL Orbit evolution with no more IAMs**
- **2008-10: Aqua A-Train Exit Plan Bill Guit (Exit predicted in 2022)**
  - The apogee of a spacecraft that has exited the constellation must be at least 2 kilometers below the minimum perigee of all current constellation members.
  - To effectively exit the constellation, Aqua and Aura's apogee must be at most 692 km.
  - Requires a 19km exit.
- **2009-10: PARASOL A-Train Project Scientists Presentation**
  - Analyzed and demonstrated a 4 km exit was safe.
- **2009-12: PARASOL Exited from the A-Train**
- **2010-02: Aqua End-Of-Mission Plan Jamie Pawloski**
- **2011-06: CloudSat Emergency Exit from the A-Train**
  - CloudSat Successful Re-ascent into the A-Train in the summer of 2012.
- **2012-10: CloudSat-Constellation-Exit-Plan Ted Sweetser**
- **2013-03: Aqua Constellation Exiting Analysis Jonathan Brown**
  - As shown in CloudSat exit plan presented at the Oct. 2012 MOWG, the requirement in the Operations Coordination Plan is overly conservative.
  - Proposed - The exiting satellite shall lower its apogee to be at least 2 km below the Constellation apogee and its perigee to be at least 2 km below the Constellation perigee, to ensure that it will avoid the Alert ZOE of all other satellites.
- **2014-10-MOWG-Envelopes and safe entries and exits Mark Vincent**
  - Proposed use of a Constellation Envelop equation to determine if "in" or "out".

Aqua A-Train Exit Plan

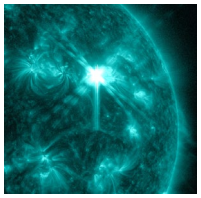
History (2015 – 2019)

KEY: YYYY-mm was an ESC MOWG Meeting

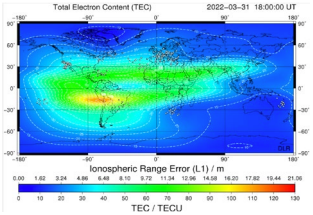
- **2015: Ops Coordination Plan for the Morning and Afternoon Constellations**
  - Safe Constellation Exit is defined by being completely outside the “Constellation Envelope”.
  - To effectively exit the Constellation, exited spacecraft maximum apogee will be always at least 4 km below the Constellation Envelope.
- **2016: CCR #17 Reduced the 4 km required separation to 2 km**
- **2016-09: Aqua Extended Mission Options Bill Guit**
- **2017-06: Aqua Extended Science Mission after the A-Train Proposed**
  - January 2022 Constellation Exit Maneuvers (CEMs) with immediate perigee lowering.
  - Near-circular exit of 4 km plus 10% safety margin (4.58 km) – requires 4 CEMs.
  - Jan/Feb 2022 Perigee Lowering Maneuvers (PLMs) – 9 PLMs planned (12.3 km).
  - Continue to collect science data after exiting.
- **2018: CloudSat Exited the A-Train (February)**
- **2018: CALIPSO Exited the A-Train (September)**
- **2018-12: Aqua and Aura IAM Improvements (fuel savings/longer missions)**
  - Aura in spring 2019, Aqua in spring 2020.
- **2019-06: Aqua After the A-Train Extended Mission**
  - Aqua Exits A-Train in January 2022 and continues to operate until 2026.
- **2019: Aqua A-Train Constellation Exit Analysis (Aug. 2019) Dave McKinley**
  - Perform the largest possible delta-SMA with the first maneuver pair
  - Perform pairs 180 degrees apart from each other

Aqua Passing GCOM-W1

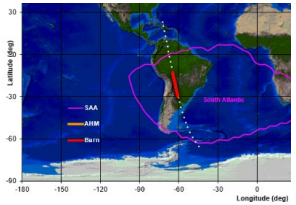
Backup & Image Credits



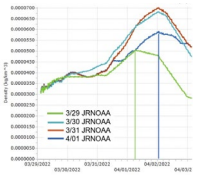
Credit: NASA's Solar Dynamics Observatory. Image shows the X1.3 solar flare's extreme ultraviolet flash on 3/30 at 17:37 UTC.



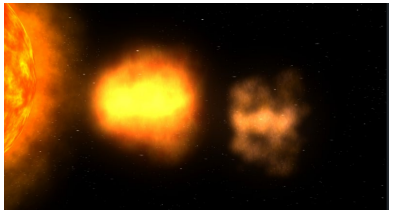
Credit: Total Electron Content (TEC) Provided by GSFC Space Weather Laboratory, Code 674 in response to ESMO's request for Space Weather assessment during Aqua Safe Mode on 3/31 at 17:59:08 UTC.TEC on 3/31 at 1800 UTC.



Credit: EOS Aqua Flight Operations Team (FOT) Anomaly Investigation. Location of Aqua Safe Mode on 3/31 at 17:59:08 UTC was in the South Atlantic Anomaly that was experiencing elevated TEC counts at the time.



Credit: EOS Aqua Flight Dynamics System (FDS) Team. Atmospheric density model predictions for 3/29/2022 thru 4/1/2022.



Credit: Cannibal Corona Mass Ejection (CME).
NASA/Goddard Space Flight Center Conceptual Image Lab.
https://svs.gsfc.nasa.gov/20067

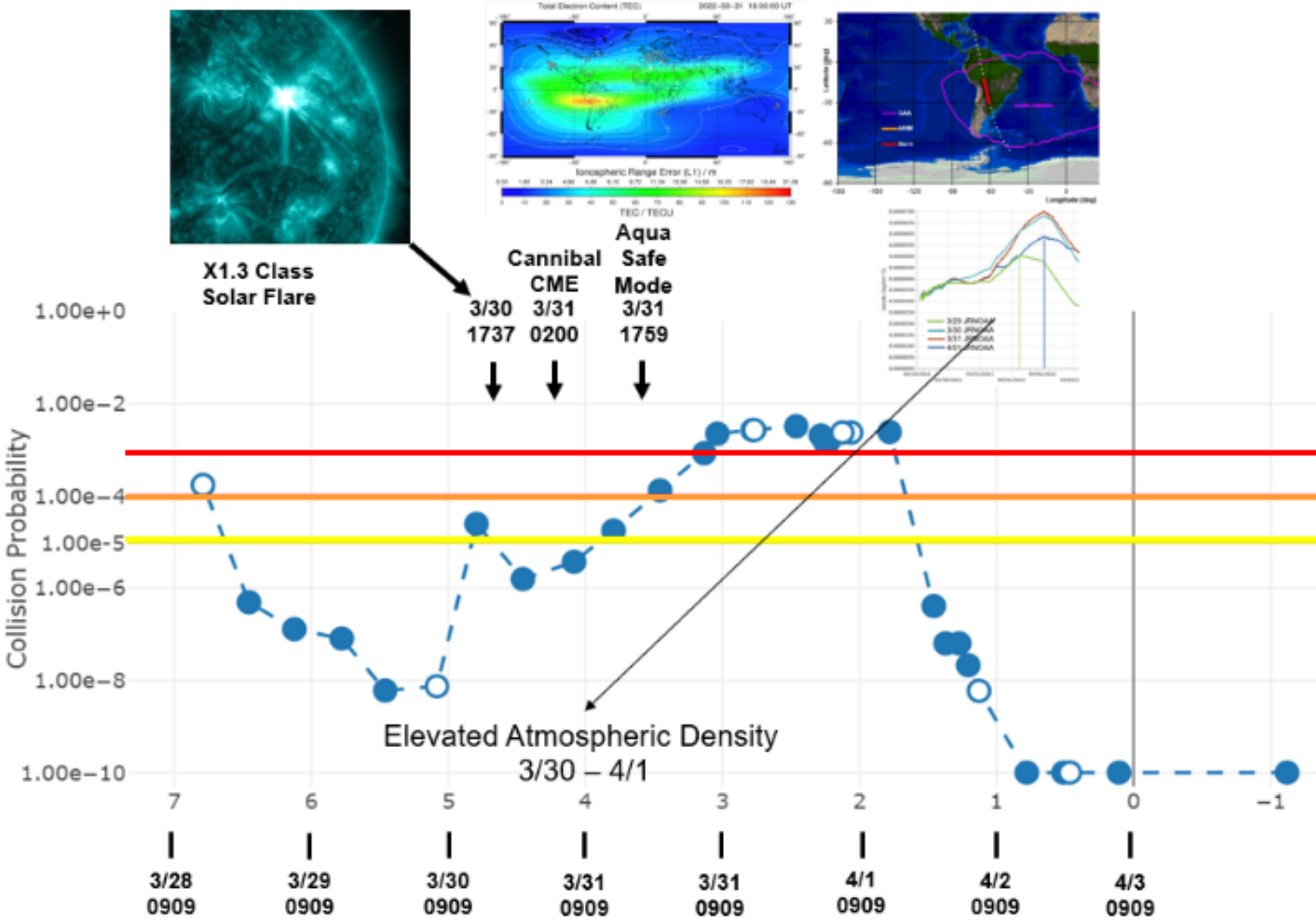
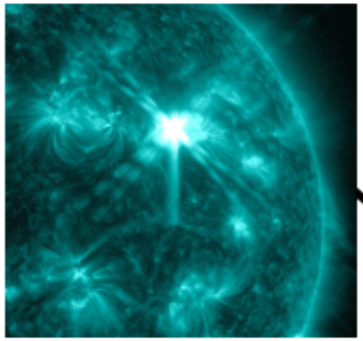


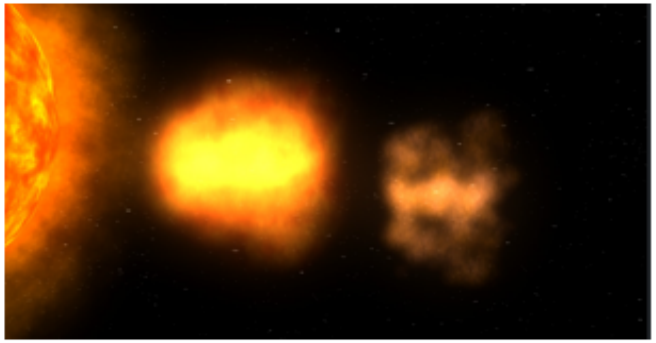
Image Credit: SpaceNav Collision Risk Management System



Cannibal CME

3/30 1737

3/31 0200



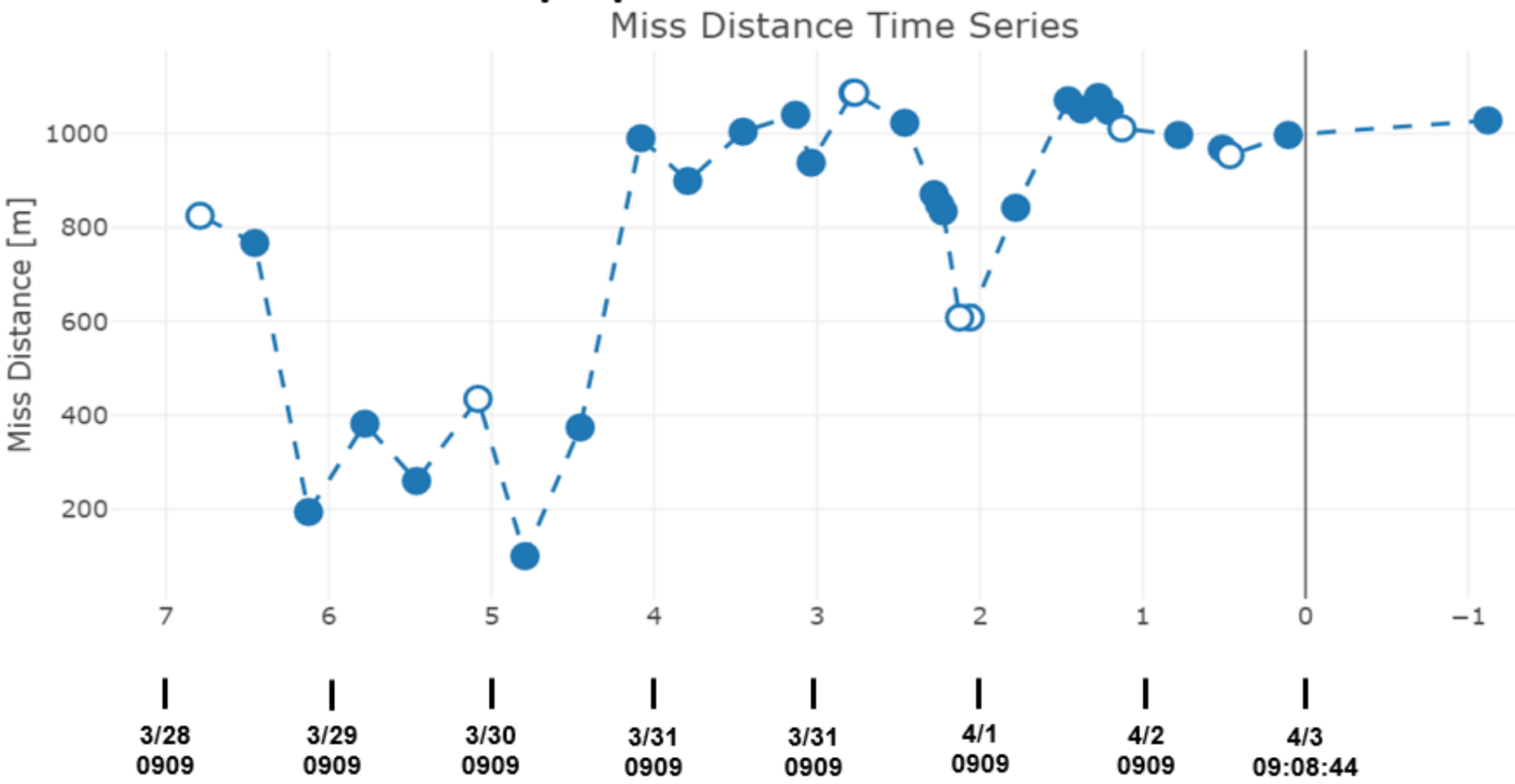
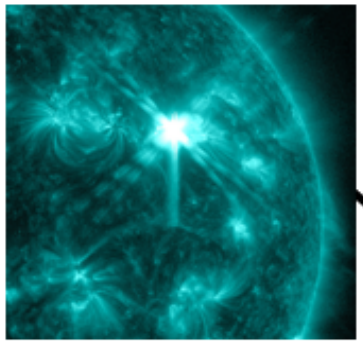
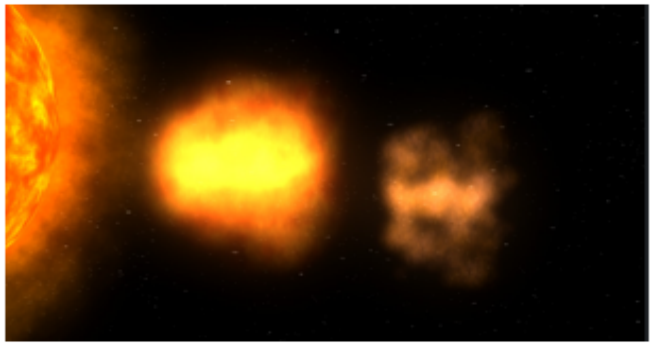


Image Credit: SpaceNav Collision Risk Management System





Cannibal CME

3/30 1737

3/31 0200

X1.3 Class Solar Flare

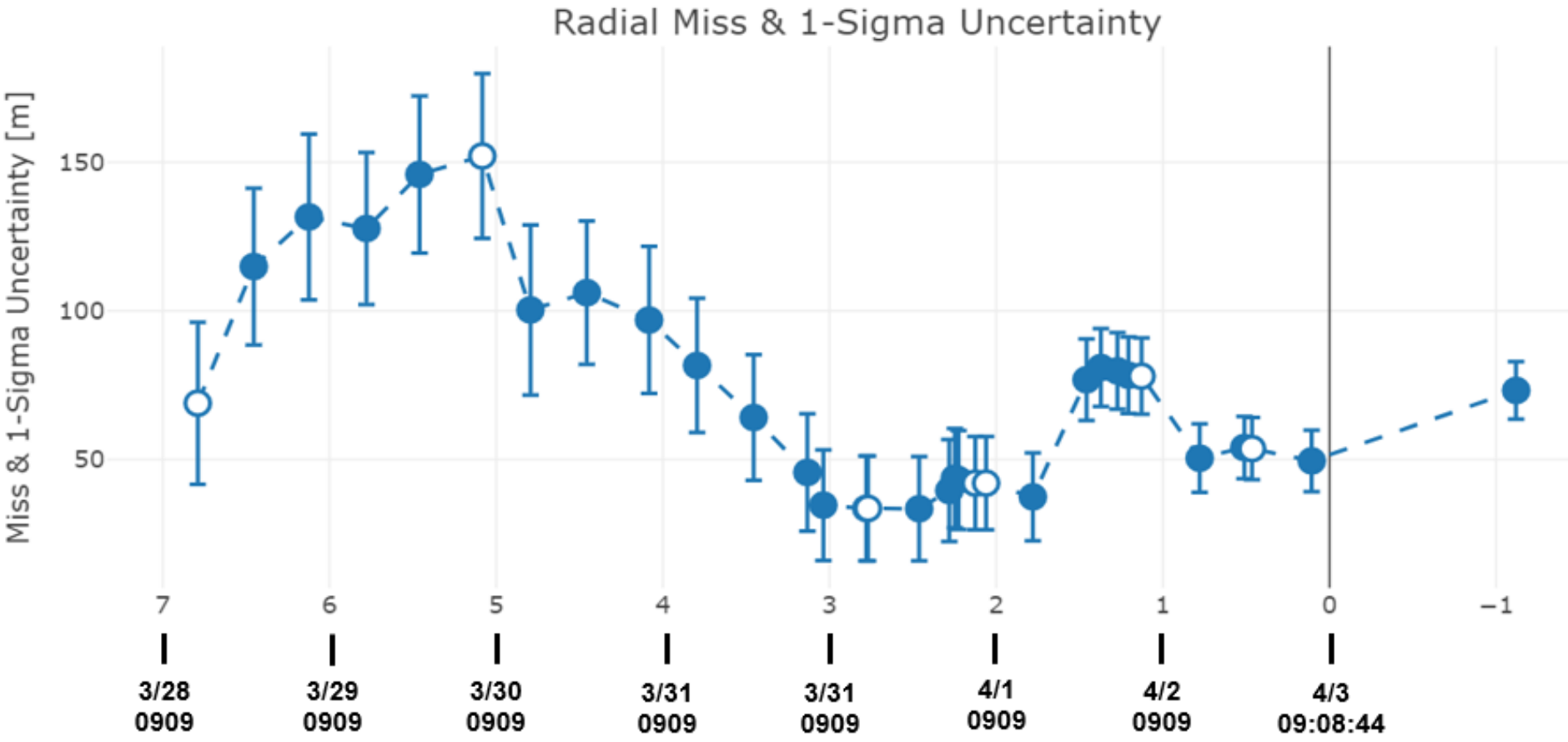
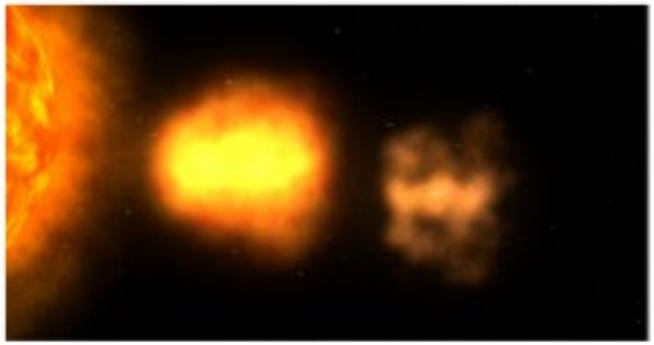


Image Credit: SpaceNav Collision Risk Management System

X1.3 Class
Solar Flare

Cannibal
CME
3/30 1737
3/31 0200



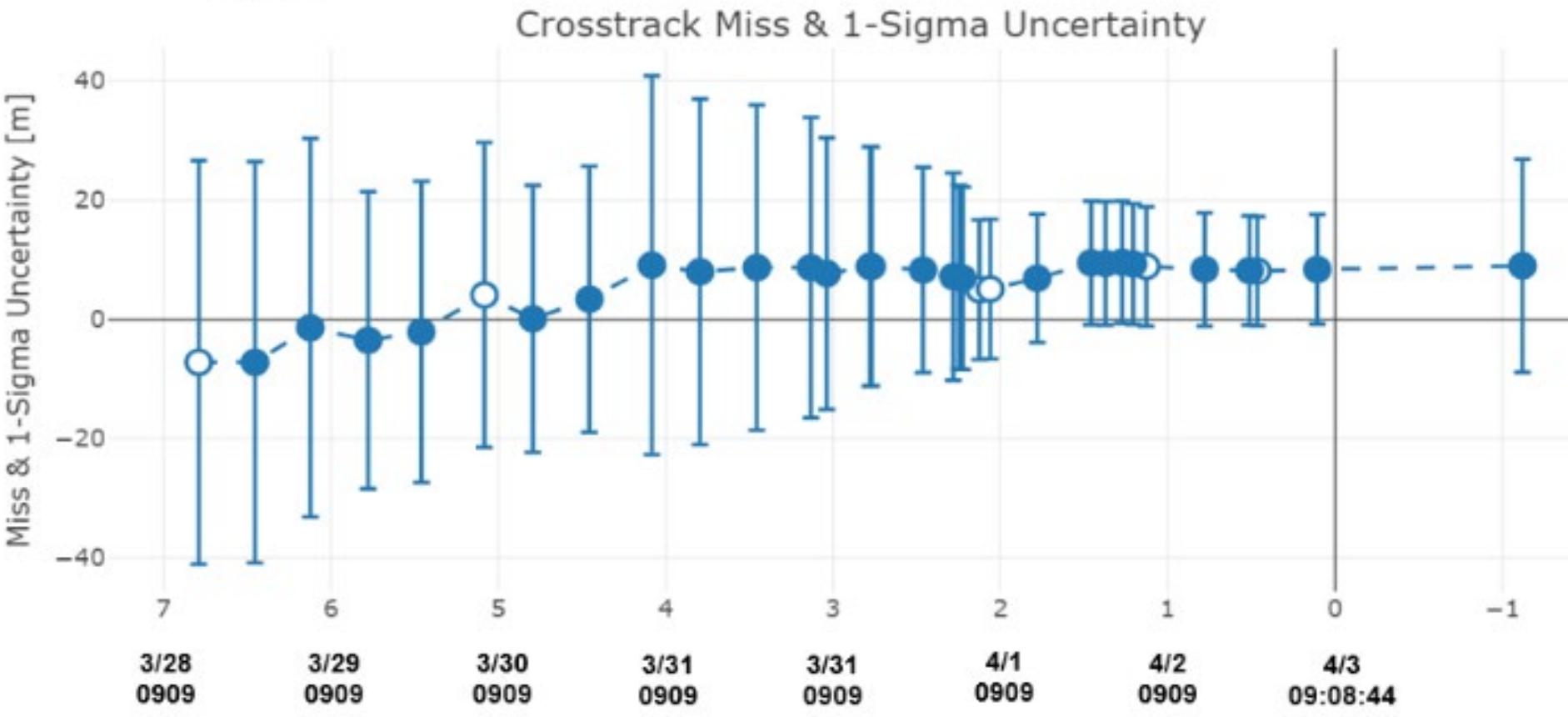
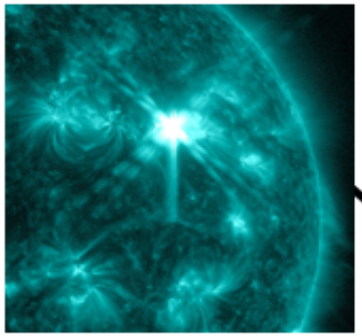
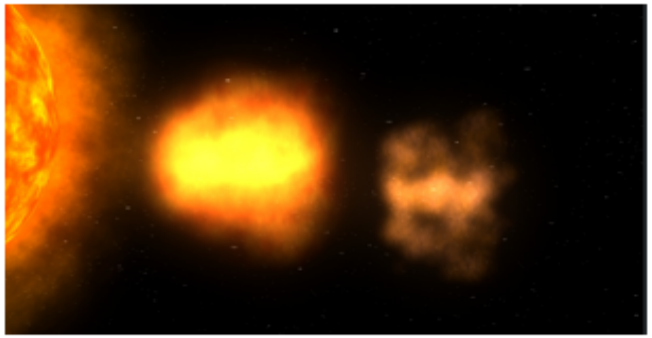


Image Credit: SpaceNav Collision Risk Management System



X1.3 Class
Solar Flare

Cannibal
CME
3/30 1737
3/31 0200



Intrack Miss & 1-Sigma Uncertainty

Miss & 1-Sigma Uncertainty [m]

4000
2000
0
−2000
−4000

7 6 5 4 3 2 1 0 −1

3/28 0909
3/29 0909
3/30 0909
3/31 0909
3/31 0909
4/1 0909
4/2 0909
4/3 09:08:44

Image Credit: SpaceNav Collision Risk Management System