CRMS Special Case Event Identification & Course of Action Concept of Operations

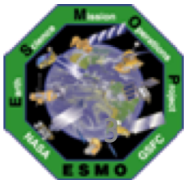## Matthew Duncan
Harrison Mast

Agenda

- Automated Data Processing Overview

- Special case event identification

- CRMS Report Flags Overview/Categories

- Statistics/Frequency of Occurrence

- Course of Action CONCEPT of OPERATIONS

- A few motivating examples

- Back-up Slides
  - Some of the supporting analysis performed to establish violation thresholds
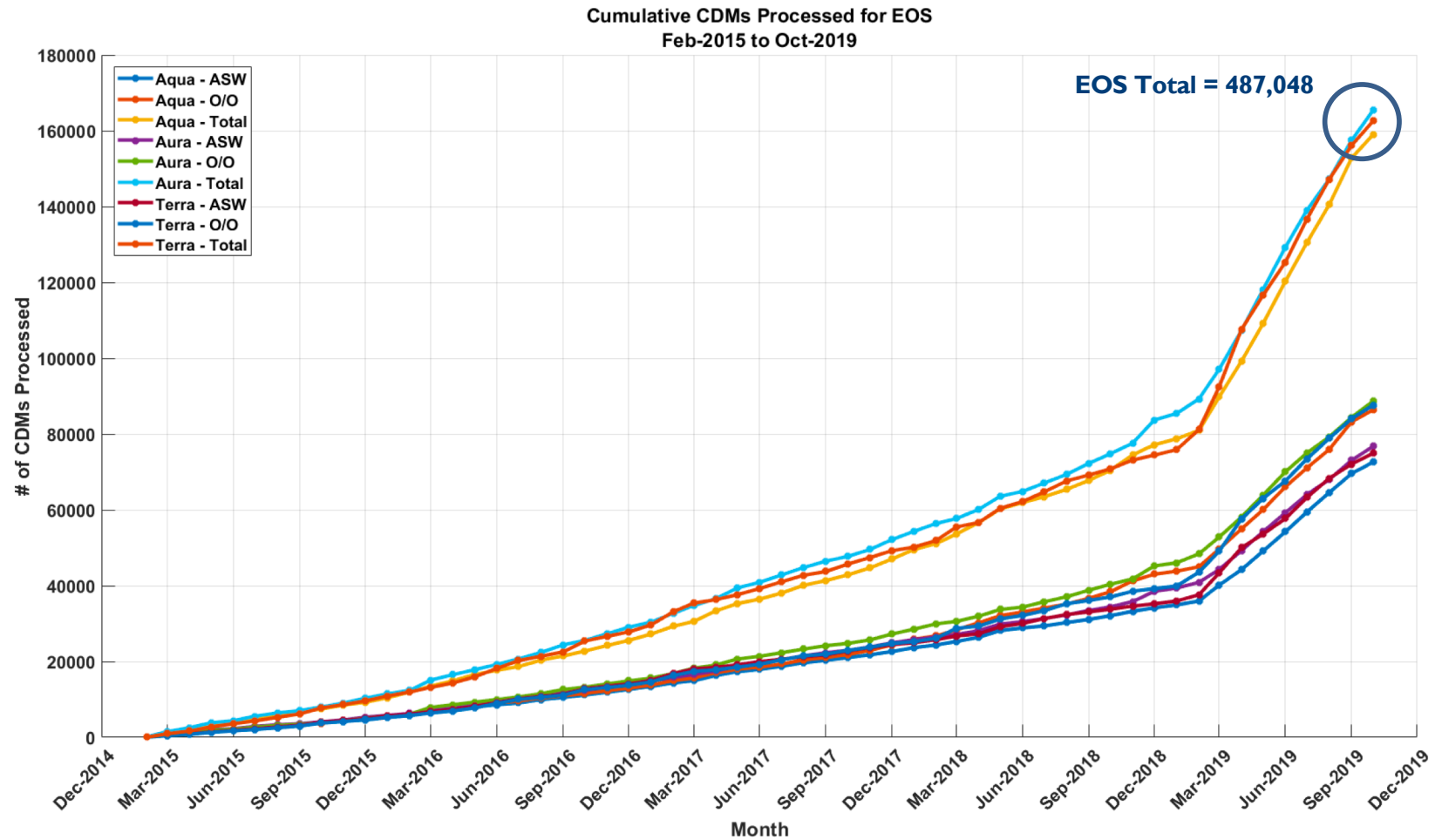
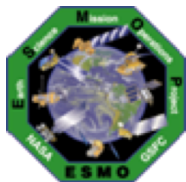SPACENAV
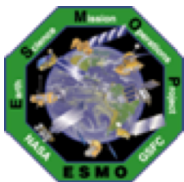
CRMS Automated Data Processing Overview

- ESMO's Collision Risk Management System (CRMS) automatically retrieves conjunction event data products from Space-Track.org

- Various reports, graphs and decision aids are generated for use in quantification and mitigation of high-risk conjunction events

- Special case events that require action are identified of the CA Summary Report
  - A companion Course of Action (COA) matrix is created; describing explicit actions to be taken

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Cumulative CDMs Processed for EOS
Feb-2015 to Oct-2019

Current Safety Screening Volume: 2x25x25 km

Number of Unique Events by Satellite Type

Legend:
- Payload (1451)
- Rocket Body (344)
- Debris (9936)
- Unknown (3029)
- TBA (29)

Percentages: 10%, < 1%, 2%, 20%, 67%
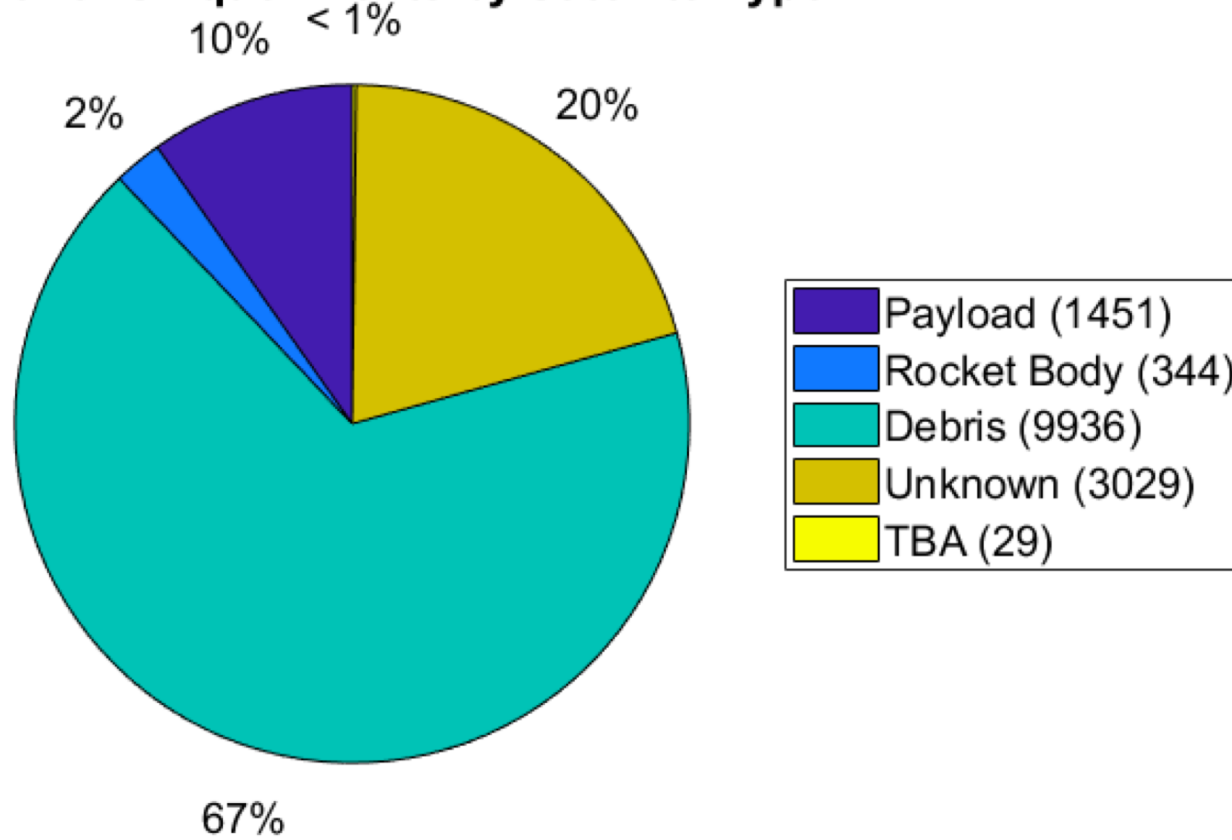
(ASW-only) Distribution Statistic for AQUA, AURA, TERRA: Feb 2015 – Oct 2019

SPACENAV
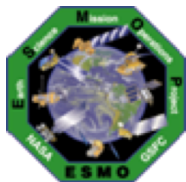
- As part of CARA devolution, ESMO created a detailed concept of operations document that describes how conjunction event processing & decision making is performed

- Included in this document is a section on special case event handling, which captures how non-nominal events are dealt with (Sect 4.3)

  - Typically requires some sort of additional analysis

- CRMS automatically identifies these special cases through the use of flags that reside on the CRMS reports

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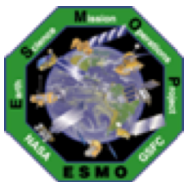
- The CRMS CA Summary Report contains risk assessment information for every close approach event
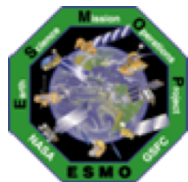 - # of active events, miss distance, collision probability, relative geometry, state uncertainty, and secondary object tracking latency.
  - The last column in the event summary table contains various flags; identifiers of anomalous data, poor OD solution, state information, etc.

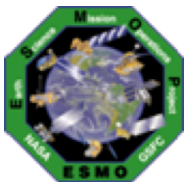| Report Gen Time to TCA [Days]	Primary Object - HBR - RIC Uncertainties [m]	Secondary Object - HBR - RIC Uncertainties [m]	Ephemeris Name: Primary Secondary	Screening Epoch	TCA [UTC]	Collision Probability	Total Miss [m]	Radial Miss & (Uncertainty) [m]	In-Track Miss & (Uncertainty) [m]	Cross-Track Miss & (Uncertainty) [m]	Relative Speed [m/s] Approach Angle [deg]	Sec Object Tracking Latency [Next Track Opp]	Flags
3.6	AQUA (27424) 15.8m [5 / 198 / 10]	IRIDIUM 33 DEB (34150) 1.5m [47 / 3336 / 10]	MEME_27424_aqua_3110000_OPS_ Aqua-2019311-NOMINAL-S00_ unclassified.txt.S00 ASW	2019-11-07 07:08:28	2019-11-10 22:43:16	5.38e-07 1:2M	11722	96 (43.1)	-10002 (1537.5)	-6110 (2967.7)	7819 62.8	6 hours 11-07 00:40 4A [11-07 08:55]	SNO COVS STC
3.6	AQUA (27424) 15.8m [4 / 220 / 4]	IRIDIUM 33 DEB (34150) 1.5m [47 / 3336 / 10]	ASW ASW	2019-11-07 07:08:37	2019-11-10 22:43:16	1.07e-06 1:934K	11278	111 (43.2)	-9624 (1540.5)	-5878 (2967.7)	7819 62.8	6 hours 11-07 00:40 4A [11-07 08:55]	PODS PNO SNO COVS STC

Flags location & identifiers

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Primary Object Flags		Secondary Object Flags		Conjunction Event Flags	
PDC (Primary - Default Covariance)	PEDR (Primary - High EDR)	SDC (Secondary - Default Covariance)	SEDR (Secondary - High EDR)	COVS (Covariance Sensitivity)	CPD (Combined Non-positive definite)
PLO (Primary - Low Observations)	PNO (Primary - New Observation)	SLO (Secondary - Low Observations)	SNO (Secondary - New Observation)	CPPD (Conjunction Plane Non-positive definite)	DPc (CRMS/CDM Delta Pc Difference)
PNS (Primary - New Solution)	PODS (Primary - OD Span)	SNS (Secondary - New Solution)	SODS (Secondary - OD Span)	M (Low Miss Distance)	RV (Low Relative Velocity)
PPD (Primary - Non-positive definite)	PRCS (Primary - Large RCS)	SPD (Secondary - Non-positive definite)	SRCS (Secondary - Large RCS)	HBRS (Pc HBR Sensitivity)	
PST (Primary - Stale Tracking)	PTC (Primary - Tasking Category Change)	SST (Secondary - Stale Tracking)	STC (Secondary - Tasking Category Change)		
PWRMS (Primary - High WRMS)	PZC (Primary - Zero Covariance)	SWRMS (Secondary - High WRMS)	SZC (Secondary - Zero Covariance)		

- CRMS automated data processing performs a series of checks and numerical comparisons for every Conjunction Data Message that is received

- Certain fields in the CDM are compared to some expected value; a flag is set if the value on the CDM is outside the expected range or fails some sort of Q/A check
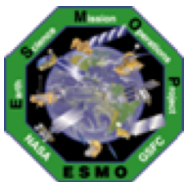
SPACENAV

| Primary Object Flags		Secondary Object Flags		Conjunction Event Flags	
PDC (Primary - Default Covariance)	PEDR (Primary - High EDR)	SDC (Secondary - Default Covariance)	SEDR (Secondary - High EDR)	COVS (Covariance Sensitivity)	CPD (Combined Non-positive definite)
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PPD (Primary - Non-positive definite)	PRCS (Primary - Large RCS)	SPD (Secondary - Non-positive definite)	SRCS (Secondary - Large RCS)	M (Low Miss Distance)	RV (Low Relative Velocity)
PST (Primary - Stale Tracking)	PTC (Primary - Tasking Category Change)	SST (Secondary - Stale Tracking)	STC (Secondary - Tasking Category Change)	HBRS (Pc HBR Sensitivity)	
PWRMS (Primary - High WRMS)	PZC (Primary - Zero Covariance)	SWRMS (Secondary - High WRMS)	SZC (Secondary - Zero Covariance)		

- Threshold Violations – Numerical comparison to some expected value
  - Thresholds determined by using historical data to determine the expected value.
    - Primary mission specific
    - Secondary object type specific (ex. Low observations threshold for debris is different than low observations threshold for a payload)
    - Some engineering judgement and operational considerations applied when determining some of the settings
- Binary Violations – Check to see if a specific field on the CDM was populated, or fails a Q/A check, or has changed since the last update

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Primary Object Flags		Secondary Object Flags		Conjunction Event Flags	
PDC (Primary - Default Covariance)	PEDR (Primary - High EDR)	SDC (Secondary - Default Covariance)	SEDR (Secondary - High EDR)	COVS (Covariance Sensitivity)	CPD (Combined Non-positive definite)
PLO (Primary - Low Observations)	PNO (Primary - New Observation)	SLO (Secondary - Low Observations)	SNO (Secondary - New Observation)	CPPD (Conjunction Plane Non-positive definite)	DPc (CRMS/CDM Delta Pc Difference)
PNS (Primary - New Solution)	PODS (Primary - OD Span)	SNS (Secondary - New Solution)	SODS (Secondary - OD Span)		
PPD (Primary - Non-positive definite)	PRCS (Primary - Large RCS)	SPD (Secondary - Non-positive definite)	SRCS (Secondary - Large RCS)	M (Low Miss Distance)	RV (Low Relative Velocity)
PST (Primary - Stale Tracking)	PTC (Primary - Tasking Category Change)	SST (Secondary - Stale Tracking)	STC (Secondary - Tasking Category Change)	HBRS (Pc HBR Sensitivity)	
PWRMS (Primary - High WRMS)	PZC (Primary - Zero Covariance)	SWRMS (Secondary - High WRMS)	SZC (Secondary - Zero Covariance)		

- ## CRMS has a total of 31 flags
  - 12 Primary Object flags, 12 Secondary flags & 7 Event flags
- ## CRMS flags are organized into 4 different categories:
  1. *Atypical Covariance* – Missing or unexpected covariance matrix was populated on the CDM.
  2. *OD Quality* - Indicators of a poor or questionable state solution
  3. *State Information* – Ancillary information for a given object
  4. *Conjunction Event Information* – Conjunction event specific; calculations determined using information from both the primary and secondary object

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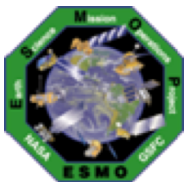
1. Atypical Covariance

- *Atypical Covariance* – Missing or unexpected covariance was contained on the CDM. Atypical covariance flags are indicators of a sparse data solution, a covariance that has been propagated forward in time for many days, or a covariance interpolation issue.

Flag Indicator	Description
Default Covariance [DC]	Indicator that the state solution was generated from a limited set of measurements or that the CDM was generated using a GP/TLE state. CRMS treats DC as zero covariance.
Non-Positive Definite Covariance [PD]	Indicator that the covariance matrix failed the positive definite test. NPD typically due to a covariance interpolation issue. Also observed in covariance matrices that have maneuver errors modeled in them
Zero Covariance [ZC]	Covariance matrix delivered with all zeros on the CDM. Mostly see this for O/O-generated solutions
Small p-value [PV]	Covariance fails the Gaussian error distribution check. Typically observed for covariance matrices that have been propagated for a long period of time. Can also be observed for objects that have large ballistic coefficients
Combined Non-PD Covariance [CPD]	Indicator that the combined covariance (Primary + Secondary) failed the positive definite test.
Conjunction Plane Non-PD Covariance [CPPD]	Indicator that the combined covariance projected into the conjunction plane failed the positive definite test.

2. OD Quality

- *OD Quality* – Indicators of a poor state solution; limited observations, or old epoch age.

Flag Indicator	Description
OD Span [ODS]	Indicator that the idealized/recommended orbit determination fit span was not used when creating the state solution. Check compares used vs. recommended. This flag is expected for objects that have recently maneuvered.
Stale Tracking [ST]	Indicator that the object hasn't been tracked for several days.
Weighted RMS [WRMS]	Indicator that the WRMS value is larger than expected for a given object.
Low Observations [LO]	Indicator that a lower number of observations were used to create the state solution for a given object.
% Residual Acceptance	Indicator that a larger number of available observations were not used when creating the state solution.

3. State Information

- *State information* – Ancillary orbital information for a given object. Used to help understand observed changes in the state solution across multiple orbit updates

| Flag Indicator	Description
High EDR [EDR]	Indicator that the object has a high susceptibility to atmospheric drag. Large predictive covariance matrices will be observed even for well tracked objects.
New Observations [NO]	Indicator that new observations have been collected and used since the previous CDM was delivered.
New Solution [NS]	Indicator that a new state solution has been generated w/out any new tracking data.
Large RCS [RCS]	Reported RCS value is larger than the expected value (for given object type).
Large State Compare [SC]	Indicator that the state difference between two adjacent solutions is larger than expected.
Tasking Category Change [TC]	Indicator that the object tasking category has changed.

4. Conjunction Event Information

- *Conjunction Event information* – Descriptor for a specific conjunction event; combination of information from both the primary and secondary objects

| Flag Indicator	Description
Pc Sensitivity to Covariance [COVS]	Indicator that the Pc calculation is sensitive to small changes in the combined covariance.
Pc Sensitivity to HBR [HBRS]	Indicator that the Pc calculation is sensitive to small changes in the combined HBR.
Pc Sensitivity – ASW vs CRMS [DPc]	Indicator that the Pc value computed by CRMS is different than the Pc value being computed by ASW.
Low Relative Velocity [RV]	Indicator that the CA event is a low speed crossing.
Low Miss Distance [M]	Indicator that the CA event is a low miss distance event.

STATISTICS/FREQUENCY OF OCCURRENCE
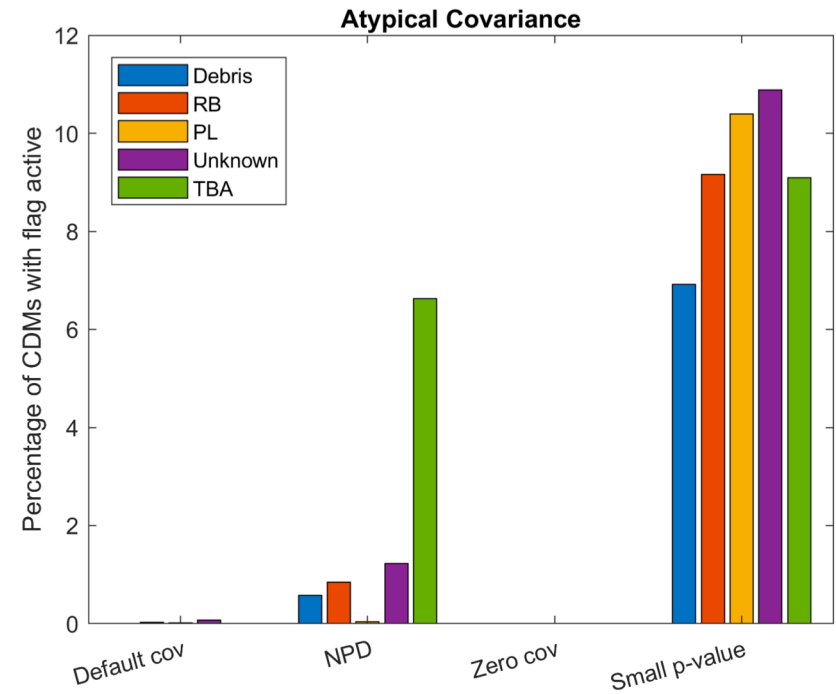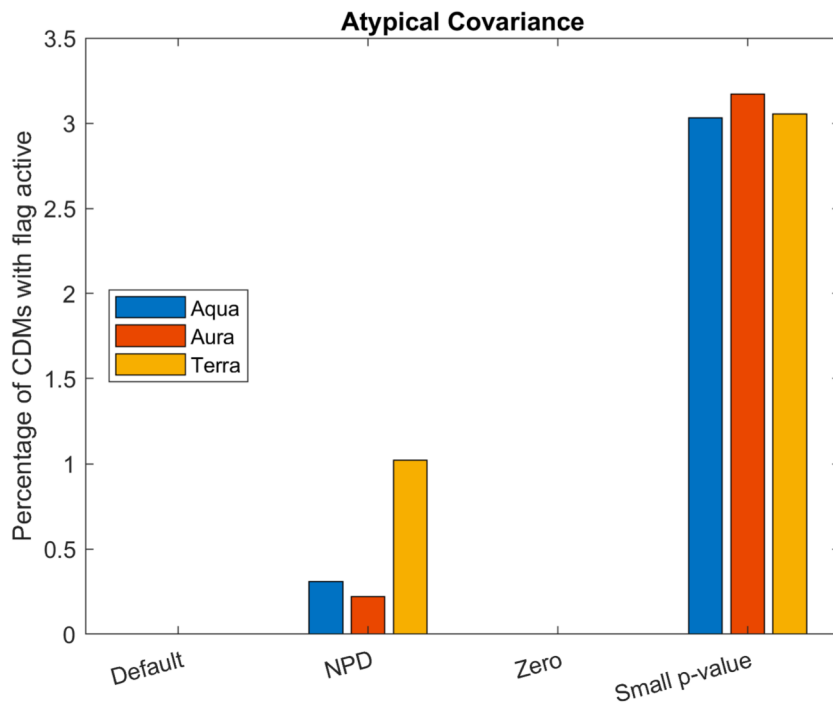
Atypical covariance can have a direct affect on quantification of the risk, since two covariance matrices are required for the Pc calculation. Atypical covariance is most likely attributed to a poor or spare orbit solution or a covariance interpolation issue.
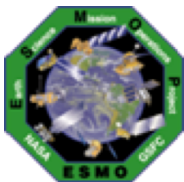
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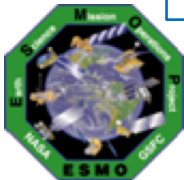
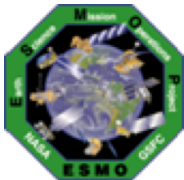# Frequency of Occurrence for Flags – OD Quality
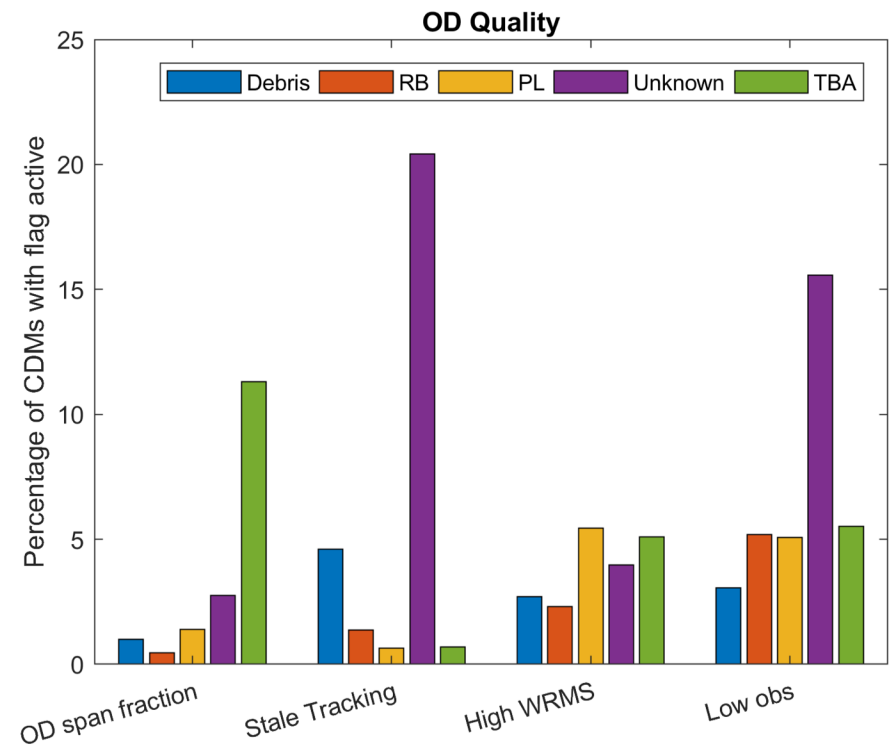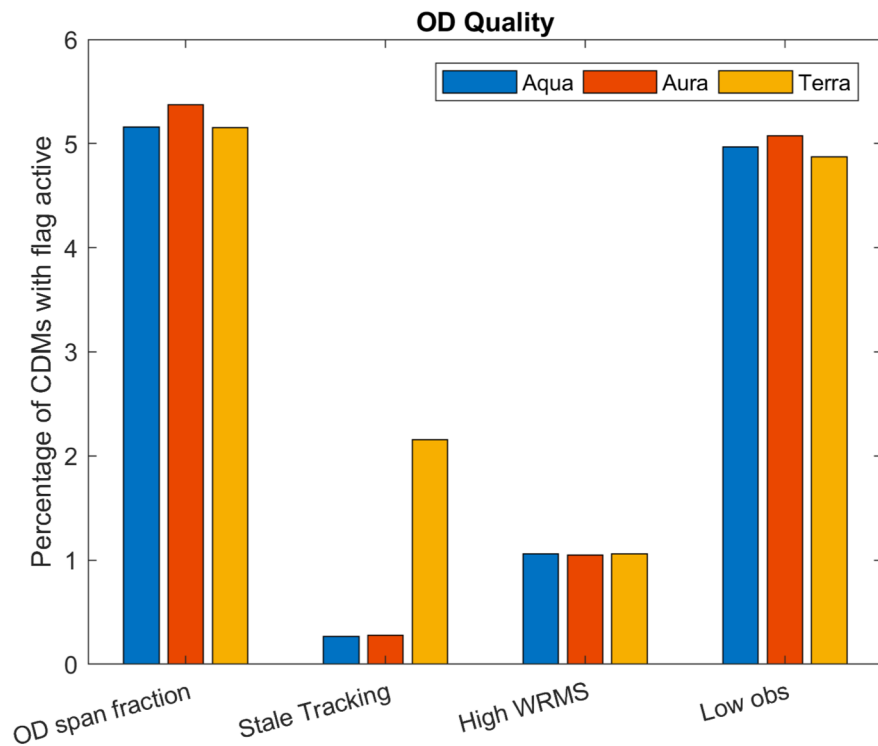
OD Quality flags are used to identify less than ideal state solutions. Threshold violations chosen so that, on average we expect to see OD quality failures ~5% of the time. For high Pc events, the CA Engineer will notify the CARA OSA to see if an improved solution can be generated.
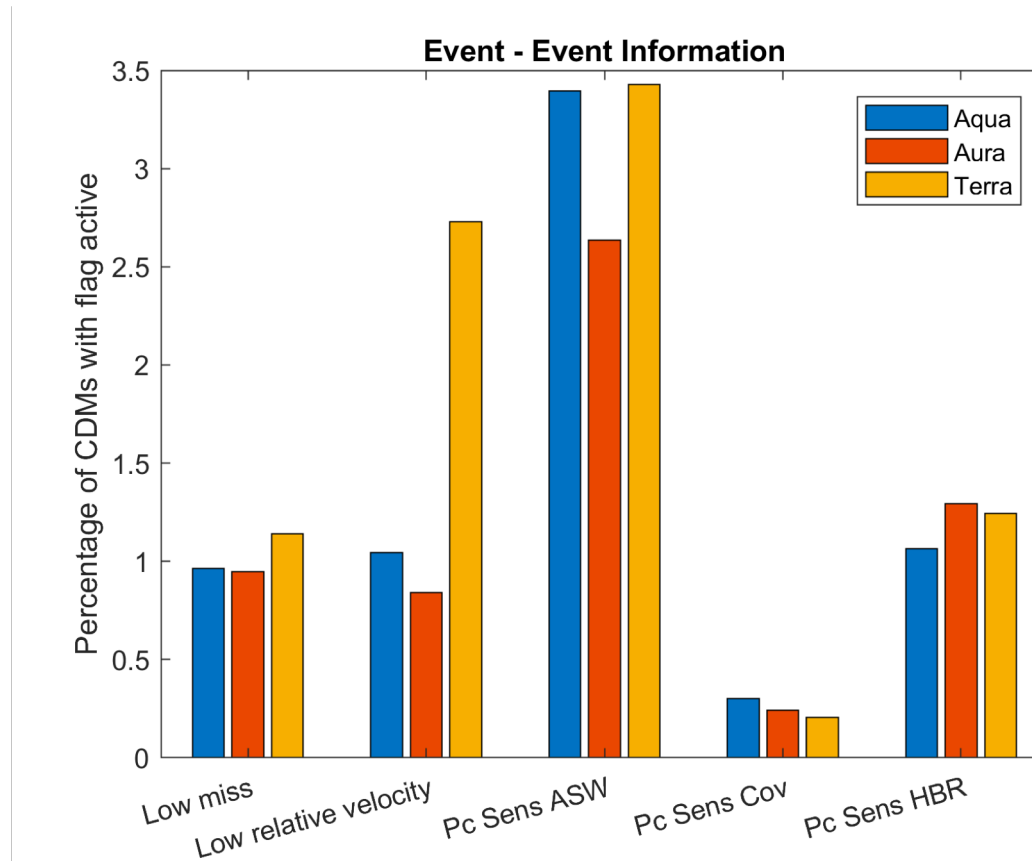
SPACENAV

# Frequency of Occurrence for Flags – State Information
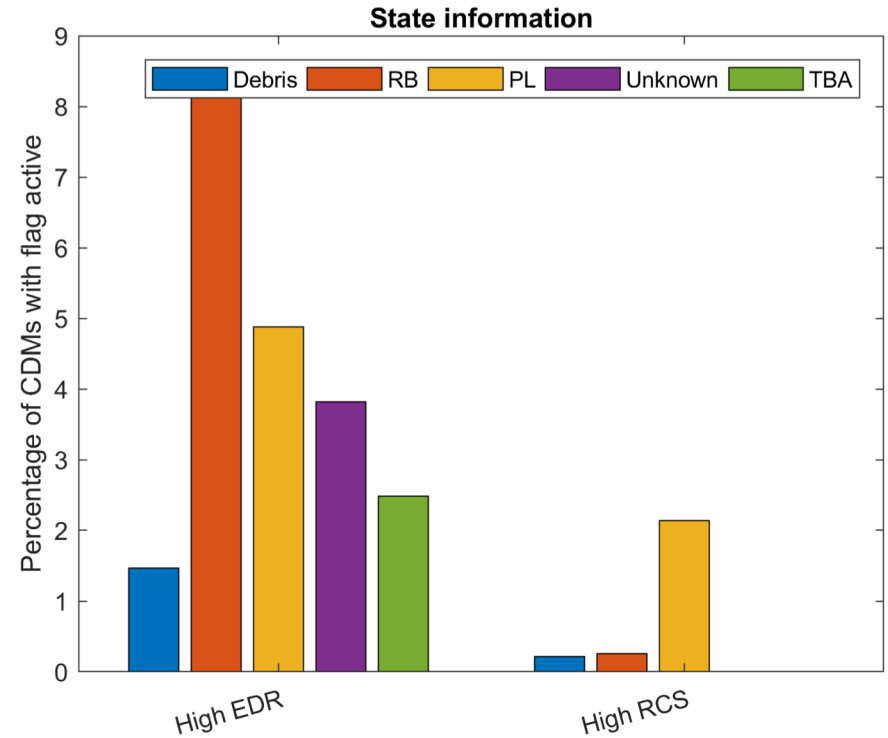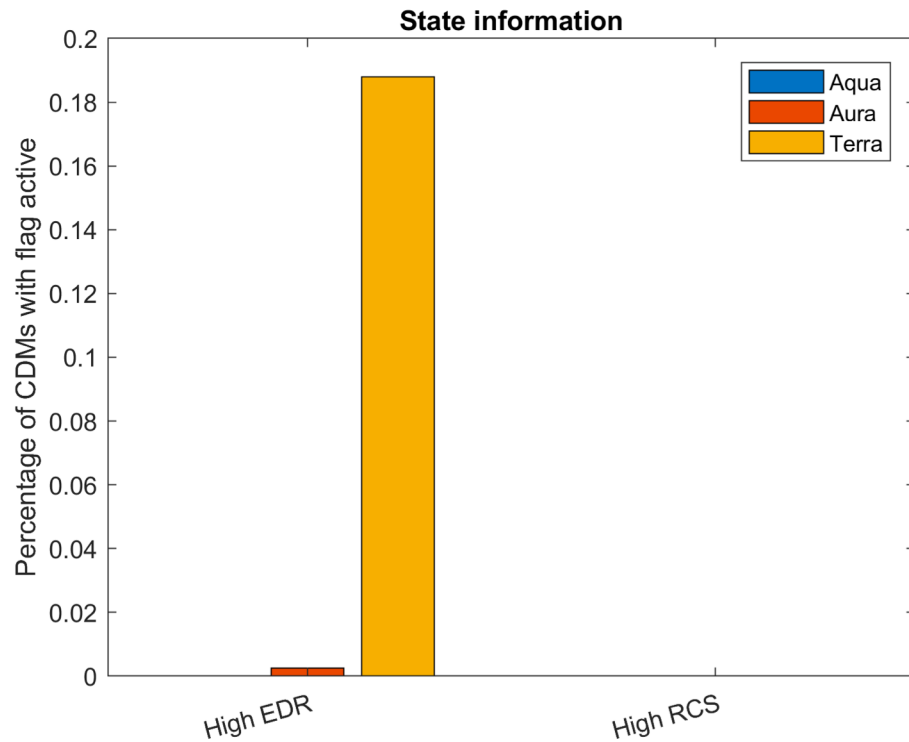
State Information flags provide ancillary orbital information for a given object. Observed changes to the state solution can be explained with help from the state information flags.

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# Frequency of Occurrence for Flags – Conjunction Event Information

Conjunction Event Information flags identify special cases where additional analysis must be performed to determine the appropriate COA. COA ranges from Monte Carlo analysis to manual maneuver planning.

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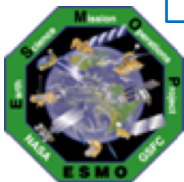
COURSE OF ACTION CONCEPT OF OPERATIONS

Course of Action - Overview

- Operational utilization of the flags and corresponding Course of Action (COA) varies –
  - Dependence on days to TCA, current Pc, specific object
  - Some flags are expected in some situations while not in others; other flags are informational and used to provide clarity

- Possible COAs to be taken
  - Perform additional analysis
  - Request addition information on the state solution
    - Cross-reference with CARA OSA HIE worklist
  - Check to see if other related flags are present
  - Wait for new data and reassess

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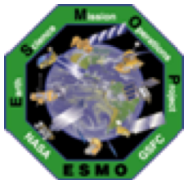
COA Matrix in CRMS [1 of 2]

- A Course of Action Matrix has been added to the CRMS Summary Report
- COA Matrix CONOPS is for the COA matrix to only contain events/flags that require explicit actions to be taken by the mission stakeholder
- Population of the COA Matrix can be configured per mission and per CRMS Flag
  - Each individual ESMO mission can decide weather or not a certain flag is to be placed in the COA Matrix
  - 'Action Required' COA language can be modified (at the flag level) per a configuration file
- Additional logic allows for further filtering when populating the COA Matrix
  - Filters: days to TCA, Pc value, and object ephemeris source (ASW, O/O or both)

Courses of Action		
Flag	**Action Required**	**Relevant Events**
RV (Low Relative Velocity)	Compute MC Pc to quantify risk.	AQUA(27424) [O/O] vs FENGYUN 1C DEB(30946) [ASW], TCA: 2019-11-07 19:37:05 AQUA(27424) [ASW] vs FENGYUN 1C DEB(30946) [ASW], TCA: 2019-11-07 19:37:05
SW (Secondary - High WRMS)	Confirm with CARA OSA that the object is tasked appropriately.	TERRA(25994) [O/O] vs PICOSAT 5(26093) [ASW], TCA: 2019-11-09 00:09:33 TERRA(25994) [ASW] vs PICOSAT 5(26093) [ASW], TCA: 2019-11-09 00:09:33
POS (Primary - OD Span)	Check to see if the OD arc was cut due to a planned maneuver. Notify CARA OSA if it appears that the obs used set was smaller than expected.	GPM(39574) [ASW] vs SPOOQY1(44332) [ASW], TCA: 2019-11-11 09:57:59 GPM(39574) [ASW] vs UNKNOWN(85262) [ASW], TCA: 2019-11-13 21:56:48

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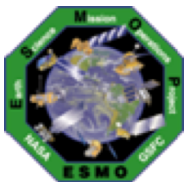
- With additional filters of Days to TCA < 4 and Pc > 1.0e-7, the expected number of event that would require some sort of action to be taken is ~ 20/week.

Average Number of Flags Per Week

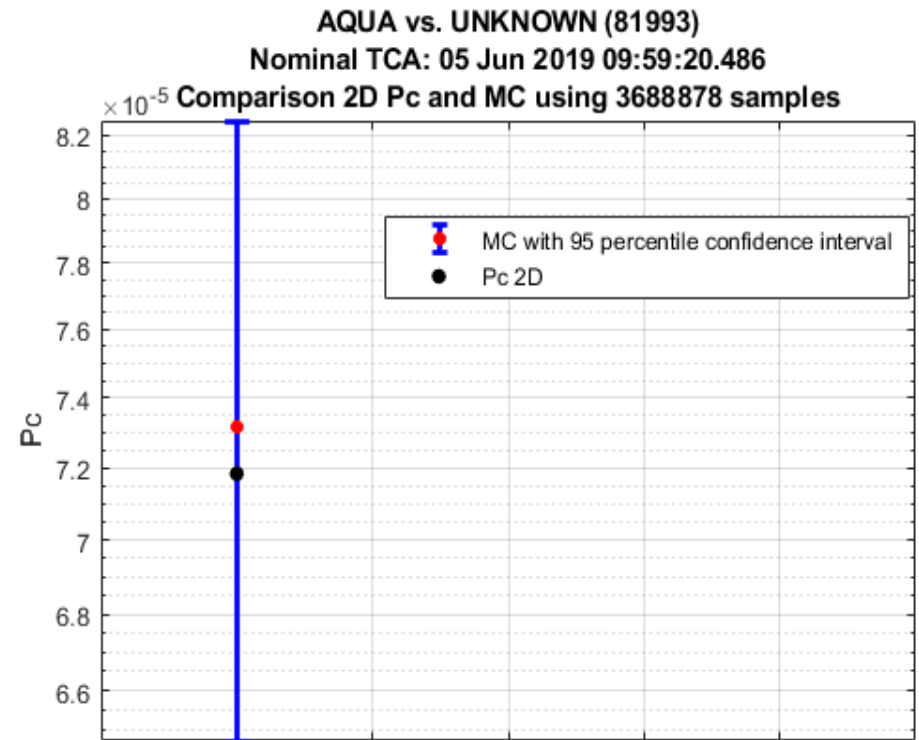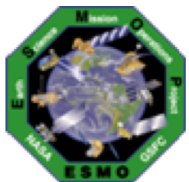SPACENAV
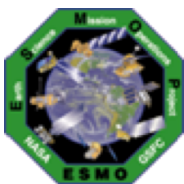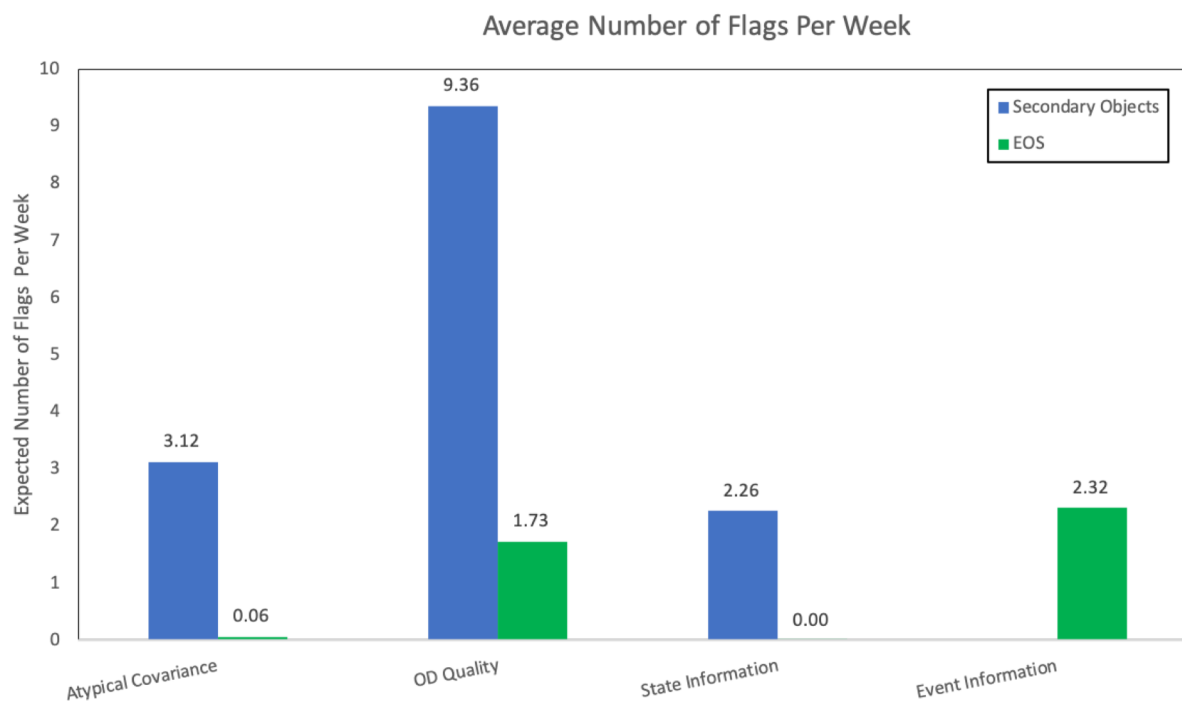
SOME OPERATIONAL EXAMPLES

Low Relative Velocity Encounter
Flag = RV

Report Gen Time to TCA [Days]	Primary Object - HBR - RIC Uncertainties [m]	Secondary Object - HBR - RIC Uncertainties [m]	Ephemeris Name: Primary Secondary	Screening Epoch	TCA [UTC]	Collision Probability	Total Miss [m]	Radial Miss & (Uncertainty) [m]	In-Track Miss & (Uncertainty) [m]	Cross-Track Miss & (Uncertainty) [m]	Relative Speed [m/s] Approach Angle [deg]	Sec Object - Tracking Latency [Next Track Opp]	Flags
-156.5	AQUA (27424) 15.8m [5 / 186 / 1]	UNKNOWN (81993) 1.5m [131 / 22969 / 15]	ASW ASW	2019-05-31 23:25:24	2019-06-05 09:59:20	7.18e-05 1:13K	831	76 (129.8)	-800 (22969.7)	-211 (106.7)	36 0.3	40 hours 05-30 07:27	RV PNO

- If the low relative velocity flag is set, the COA is to compute the collision probability via Monte Carlo simulation to quantify the collision risk
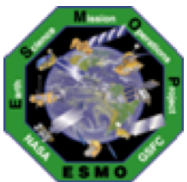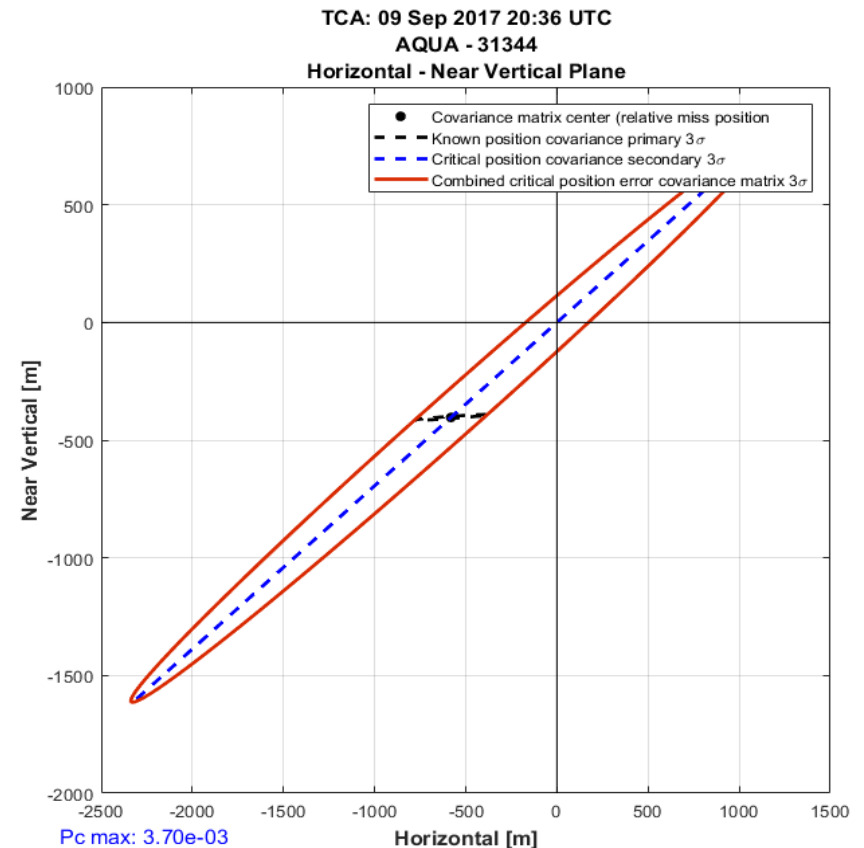 – COA required for events with a Pc > 1.0e-7 and days to TCA<3

AQUA vs. UNKNOWN (81993)
Nominal TCA: 05 Jun 2019 09:59:20.486
$\times 10^{-5}$ Comparison 2D Pc and MC using 3688878 samples

Legend:
- MC with 95 percentile confidence interval
- Pc 2D

Default Covariance – Secondary
Flag = SDC

Report Gen Time to TCA [Days]	Primary Object - HBR - RIC Uncertainties [m]	Secondary Object - HBR - RIC Uncertainties [m]	Ephemeris Name: Primary Secondary	Screening Epoch	TCA [UTC]	Collision Probability	Total Miss [m]	Radial Miss & (Uncertainty) [m]	In-Track Miss & (Uncertainty) [m]	Cross-Track Miss & (Uncertainty) [m]	Relative Speed [m/s] Approach Angle [deg]	Sec Object - Tracking Latency [Next Track Opp]	Flags
-790.1	AQUA (27424) 15.8m [2 / 433 / 2]	FENGYUN 1C DEB (31344) 1.5m [63781364 / 63781364 / 63781364]	ASW ASW	2017-09-06 06:56:30	2017-09-09 20:36:57	0.00e+00	707	-403 (63781400.0)	93 (63781400.0)	-573 (63781400.0)	14802 162.4	258 hours 08-26 13:16	PNO SDC SODS SLO SST

- If the default covariance flag is set, the COA is to compute the Max Pc and perform manual maneuver planning if Max Pc is above the maneuver execution threshold. Notify CARA OSAs that a default covariance was received and check to see if situation can be resolved by improving the OD solution
  - COA required for events with a time to TCA < 3 days (or at analyst discretion)

TCA: 09 Sep 2017 20:36 UTC
AQUA - 31344
Horizontal - Near Vertical Plane

- Covariance matrix center (relative miss position
- - Known position covariance primary 3σ
- - Critical position covariance secondary 3σ
- Combined critical position error covariance matrix 3σ

Pc max: 3.70e-03
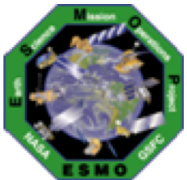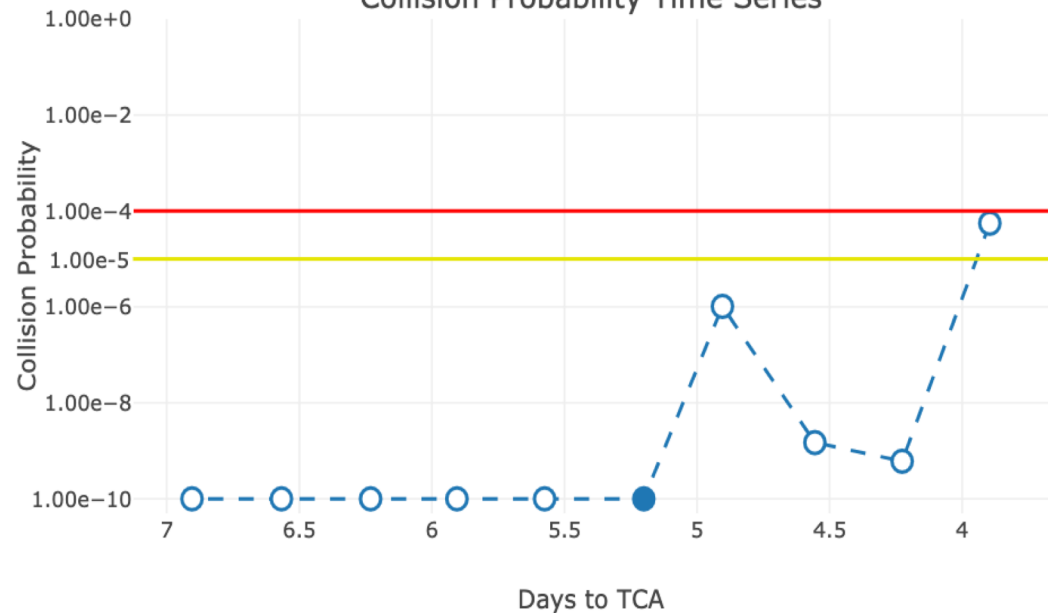
Near Vertical [m]

Horizontal [m]

New Solution – Secondary Flag = SNS

Report Gen Time to TCA [Days]	Primary Object - HBR - RIC Uncertainties [m]	Secondary Object - HBR - RIC Uncertainties [m]	Ephemeris Name: Primary Secondary	Screening Epoch	TCA [UTC]	Collision Probability	Total Miss [m]	Radial Miss & (Uncertainty) [m]	In-Track Miss & (Uncertainty) [m]	Cross-Track Miss & (Uncertainty) [m]	Relative Speed [m/s] Approach Angle [deg]	Sec Object - Tracking Latency [Next Track Opp]	Flags
-11.4	AURA (28376) 15.6m [4 / 45 / 2]	UNKNOWN (87408) 1.5m [17 / 525 / 34]	ASW ASW	2019-10-27 06:39:28	2019-10-28 12:44:28	1.55e-02 1:65	181	1 (17.2)	-156 (261.6)	91 (458.4)	7719 62.0	14 hours 10-26 16:54	M PNO SNS

- The Secondary New Solution flag indicates that a new orbit solution was generated without any new tracking data. Helps to clarify why observed changes to the CA numbers changed. The COA is to confirm that a good OD solution has been generated.

TCA: 2019-09-16 20:07:58
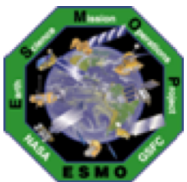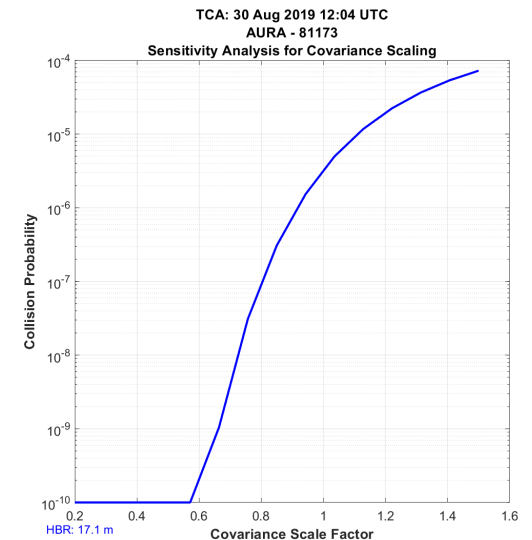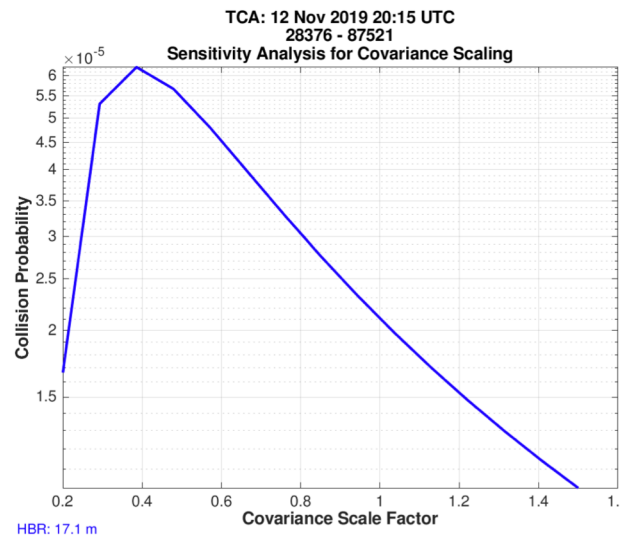AQUA (27424) - UNKNOWN (81436)
Collision Probability Time Series

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Pc Sensitivity – Covariance Flag = COVS

Report Gen Time to TCA [Days]	Primary Object - HBR - RIC Uncertainties [m]	Secondary Object - HBR - RIC Uncertainties [m]	Ephemeris Name: Primary Secondary	Screening Epoch	TCA [UTC]	Collision Probability	Total Miss [m]	Radial Miss & (Uncertainty) [m]	In-Track Miss & (Uncertainty) [m]	Cross-Track Miss & (Uncertainty) [m]	Relative Speed [m/s] Approach Angle [deg]	Sec Object - Tracking Latency [Next Track Opp]	Flags
-70.5	AURA (28376) 15.6m [4 / 32 / 2]	UNKNOWN (81173) 1.5m [187 / 320 / 170]	ASW ASW	2019-08-28 22:09:20	2019-08-30 12:04:18	3.31e-06 1:302K	1215	696 (186.5)	-789 (222.0)	-608 (288.5)	9222 75.6	39 hours 08-27 07:11	SLO PNO COVS STC

- **The Covariance Sensitivity flag indicates that the Pc value is sensitive to small changes to the combined covariance. The COA is to generate Pc sensitivity graphs to determine expected Pc direction.**
  - The COA is required for events with a time to TCA < 3 days and a Pc > 1.0e-7


TCA: 30 Aug 2019 12:04 UTC
AURA - 81173
Sensitivity Analysis for Covariance Scaling
HBR: 17.1 m

TCA: 12 Nov 2019 20:15 UTC
28376 - 87521
Sensitivity Analysis for Covariance Scaling
HBR: 17.1 m

SPACENAV

BACKUP SLIDES

METHODOLOGY FOR DETERMINING THRESHOLD SETTINGS -EXAMPLE

Secondary Object Stale Tracking – Threshold Violation Determination

75 - 95 percentile:	Debris	0.95 - 3.96	R/B	0.27 - 0.55
	Payload	0.25 - 0.55	Unknown	3.43 - 13.93
	TBA	0.43 - 0.75	Combined	1.03 - 5.43
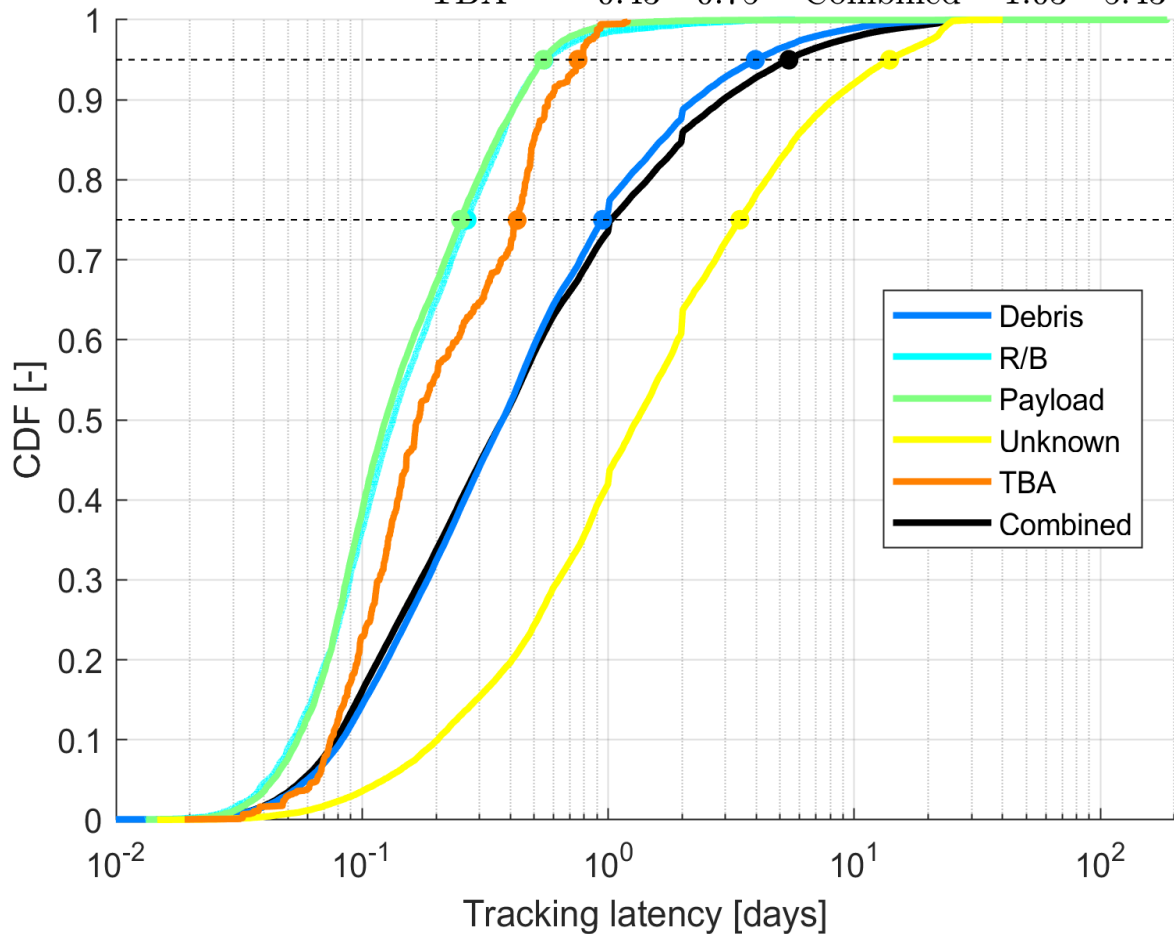
Operational Setting

Object	CRMS Flag Threshold
Debris	4.0
R/B	1.0
Payload	1.0
Unknown	4.0
TBA	1.0

Statistics collected over 2015 - 2019

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