NASA Conjunction Assessment Risk Analysis (CARA) Updated Requirements Architecture

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Agenda and Overview

- **Introduction**
  - Background, motivation and objectives
- **Current CARA operations process**
  - Current CARA operations process
  - Automated and Manual tools
  - CAS System
- **Process Updates and Supporting Analysis**
- **Operations Devolution**
- **Conclusions**

Background, Motivation and Objectives

- **Background: CARA History**
  - Initiated in January 2005 to protect the Agency's unmanned spacecraft from collision with on-orbit objects
  - Currently, supports about 70 operational Agency's assets
  - Located at the NASA Goddard Space Flight Center in Greenbelt, MD

- **Motivation for an updated requirements architecture:**
  - Recent developments in SSA and Commercial Space
    - Constellations launches: 100s to 1000s per constellation
    - Space Fence Radar: Sensitivity increase of the Space Surveillance Network (SSN) from current detection of 10cm in Low-Earth Orbit (LEO) to 5cm

- **Objectives**
  - Improvements to existing process
  - An extensive evaluation initiative to re-examine
    - risk assessment algorithms and techniques,
    - develop needed improvements and
    - assemble analysis-based operational requirements
  - Summarize the technical challenges encountered

Detailed process updates to some of the technical challenges will be presented in this CARA special session

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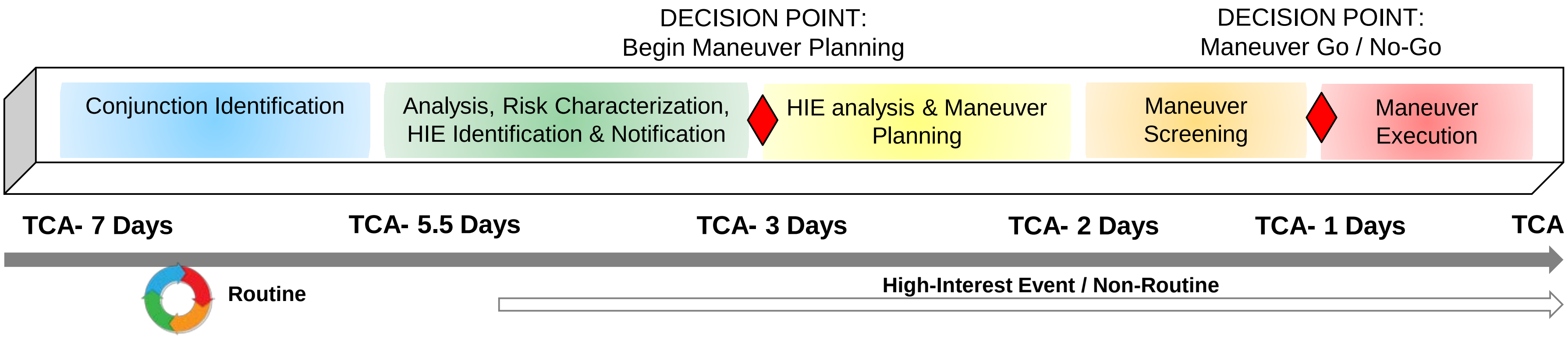
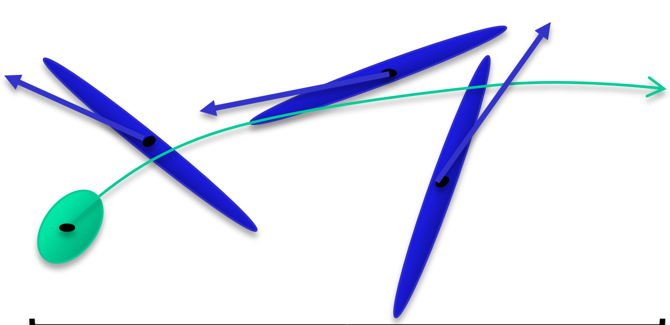
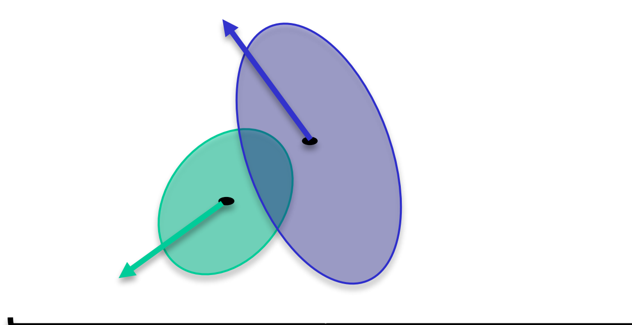
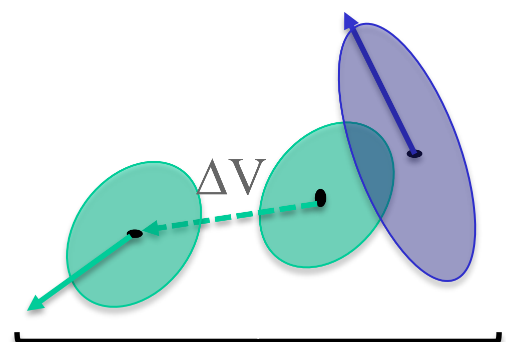
CARA Operations Process Overview

CARA Process Workflow









Conjunction Assessment (CA) is the process of identifying close approaches between two orbiting objects; sometimes called conjunction "screening"

The **18th Space Control Squadron** at Vandenberg AFB, maintains the high accuracy catalog of space objects, screens CARA-supported assets against the catalog, performs OD/tasking, and generates close approach data

CA Risk Analysis (CARA) is the process of assessing collision risk and assisting satellites plan maneuvers to mitigate that risk, if warranted

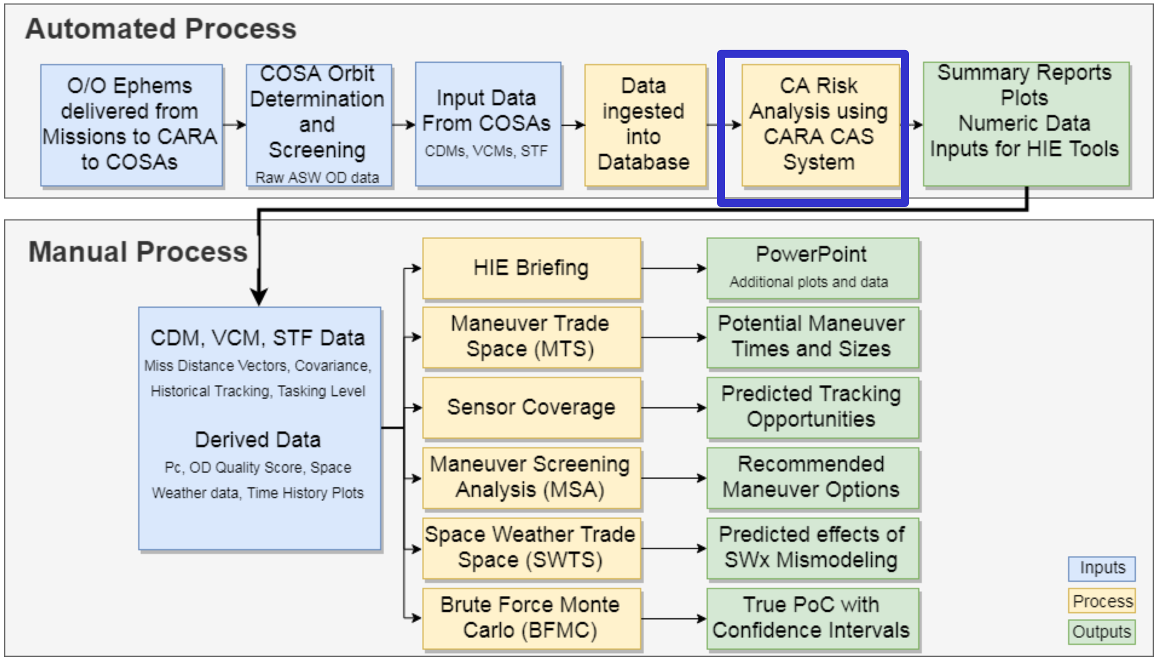
The **CARA** Team at NASA GSFC serves all NASA operational uncrewed satellites, and is a service provider for some other external agencies/organizations

Collision Avoidance (COLA) is the process of executing mitigative action, typically in the form of an orbital maneuver, to reduce collision risk

Each satellite **Owner/Operator (O/O)** – mission management, flight dynamics, and flight operations – are responsible for making maneuver decisions and executing the maneuvers

Automated and Manual Process

- **The CARA workflow has both automated and manual components that:**
  - ingest inputs
  - processes data: parsing and algorithmic implementation
  - provides output: numeric data, plots, and reports

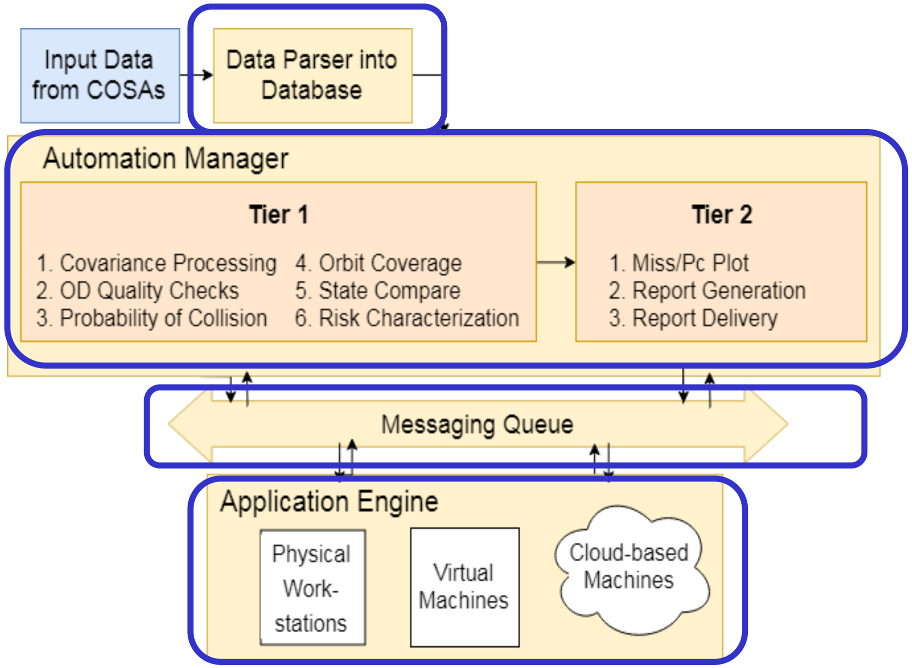


CAS Automation Process Flow

- **Conjunction Assessment System (CAS) processes:**
  - the Conjunction Data Messages (CDMs) and
  - the Sensor Tasking Files (STF) files

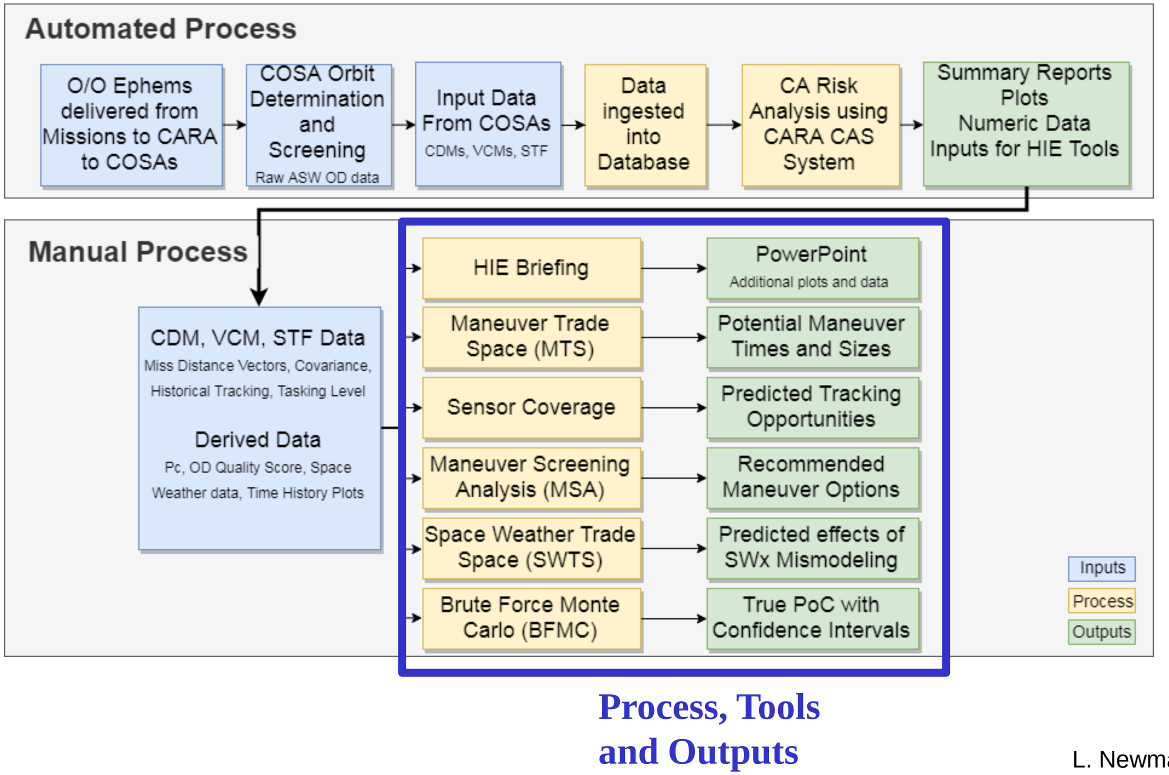
- **CAS contains 4 main parts:**
  - Data parser, Automation Manager, a Messaging Queue, and Application Engines

- **Services from Automation Manager:**
  - Covariance Processing
  - OD quality
  - Probability of Collision (Pc)
  - State Compare
  - Risk Characterization
  - Report Generation and
  - Report Distribution



Automated and Manual Process

- **The improvements to the existing risk assessment algorithms and techniques are addressed**
  - throughout the conjunction assessment & risk analysis of CAS and
  - the manual processing of CAS' output data for decision making



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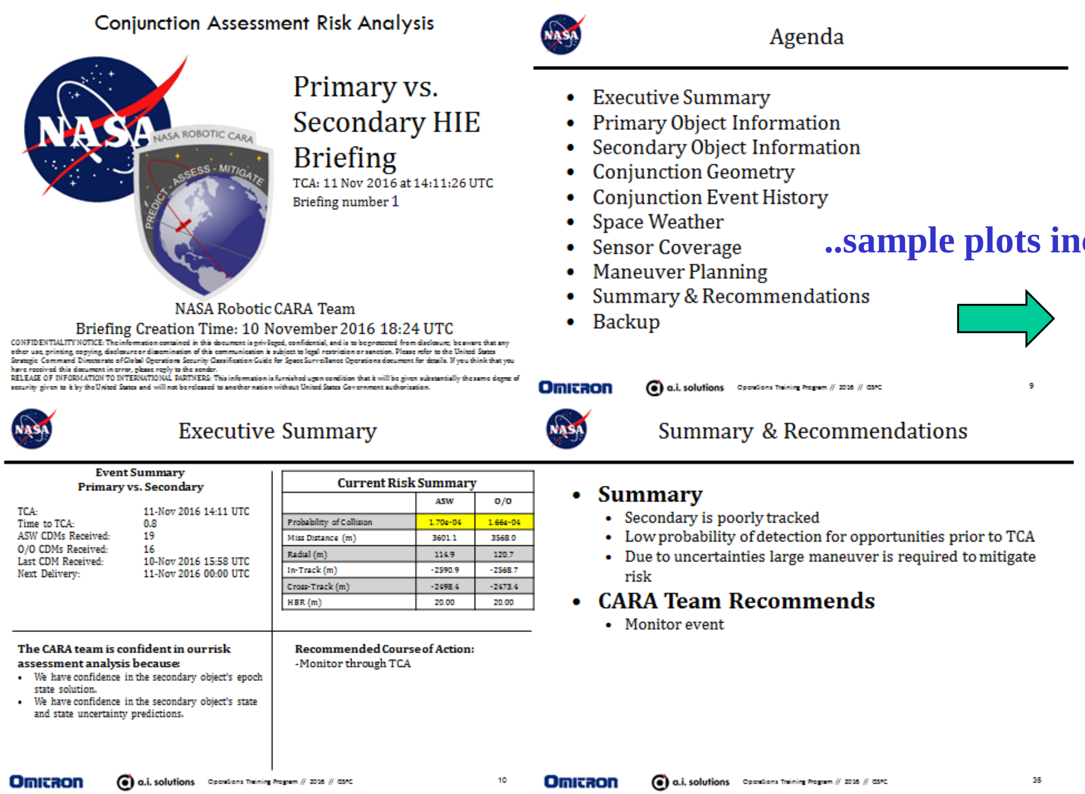
Process Updates and Supporting Analysis

- **HIE Briefing**

HIE Briefing	→	PowerPoint Additional plots and data


Conjunction Assessment Risk Analysis

Primary vs. Secondary HIE Briefing

TCA: 11 Nov 2016 at 14:11:26 UTC

Briefing number 1

NASA Robotic CARA Team

Briefing Creation Time: 10 November 2016 18:24 UTC

Agenda

- Executive Summary
- Primary Object Information
- Secondary Object Information
- Conjunction Geometry
- Conjunction Event History
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- Sensor Coverage
- Maneuver Planning
- Summary & Recommendations
- Backup

Executive Summary

Event Summary
Primary vs. Secondary

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Current Risk Summary

	ASW	O/O
Probability of Collision	1.70e-04	1.66e-04
Miss Distance (m)	3601.1	3568.0
Radial (m)	114.9	120.7
In-Track (m)	-2590.9	-2568.7
Cross-Track (m)	-2498.4	-2473.4
HBR (m)	20.00	20.00

The CARA team is confident in our risk assessment analysis because:

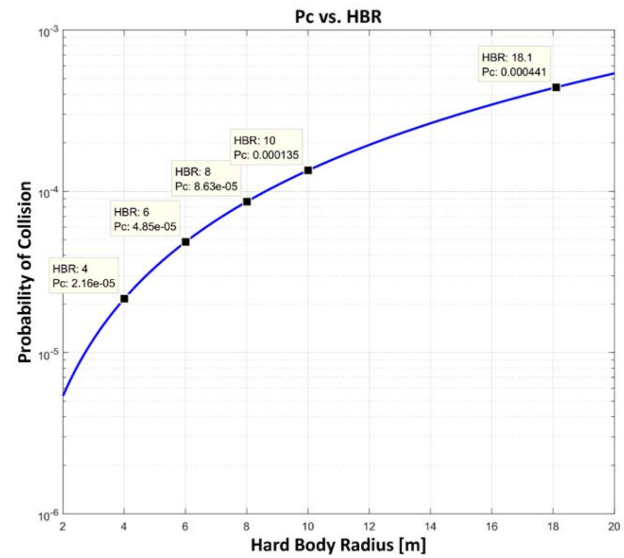
- We have confidence in the secondary object's epoch state solution.
- We have confidence in the secondary object's state and state uncertainty predictions.

Recommended Course of Action:
-Monitor through TCA

Summary & Recommendations

- **Summary**
  - Secondary is poorly tracked
  - Low probability of detection for opportunities prior to TCA
  - Due to uncertainties large maneuver is required to mitigate risk
- **CARA Team Recommends**
  - Monitor event

..sample plots include



Pc vs HBR Tool:
Varying HBR significantly varies the Pc

Process Update:
(1) Accurate approaches for setting HBR

PowerPoint presentation sample deck of an HIE Briefing that provides technical input for decision making.

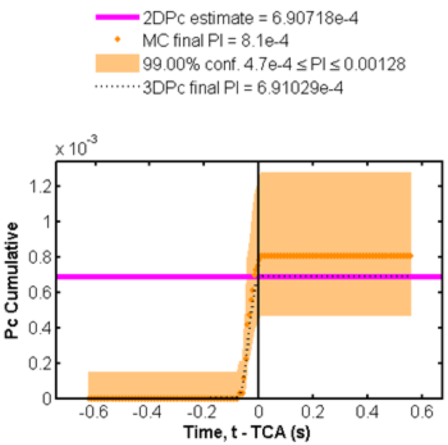
Process Updates and Supporting Analysis

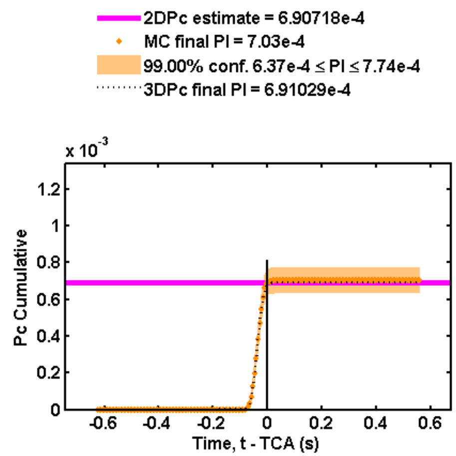
- **MSA and BFMC**

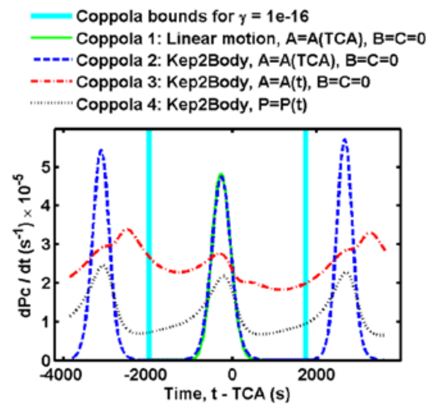
Process Update:
(2) Using BFMC to accurately assess Repeating Conjunctions

Maneuver Screening Analysis (MSA) → Recommended Maneuver Options

Brute Force Monte Carlo (BFMC) → True Pc with Confidence Intervals







Two output plots are shown here using different numbers of trials. The left plot used 3.4E6 trials compared to 1.01E6 trials on the right. The increased number of trials reduced the 99% confidence interval. Both show the nominal 2D Pc within the confidence interval.

This strain of Monte Carlo calculation, which works with the TCA states and covariances but with the state uncertainty sampling performed in equinoctial elements, <u>is being integrated with the NASA automated conjunction assessment system so that it can be automatically invoked in those situations in which the 2-D Pc is judged to be inadequate and for which Monte Carlo from epoch is not necessary.</u>

Process Updates and Supporting Analysis

- **HIE Briefings**

HIE Briefing → PowerPoint
Additional plots and data

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..sample report

Summary & Recommendations

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PowerPoint presentation sample deck of an HIE Briefing that provides technical input for decision making.

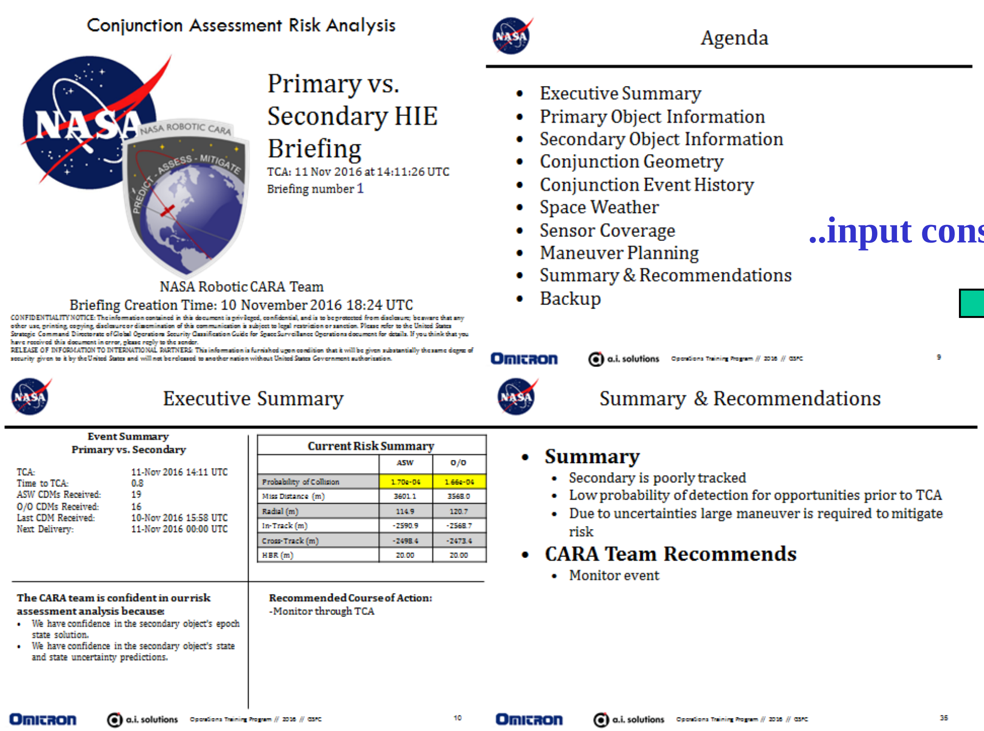
The use of Pc and other event data as a basis for CA recommendations.

Process Update:
(3) Collision Probability, Possibility and Plausibility

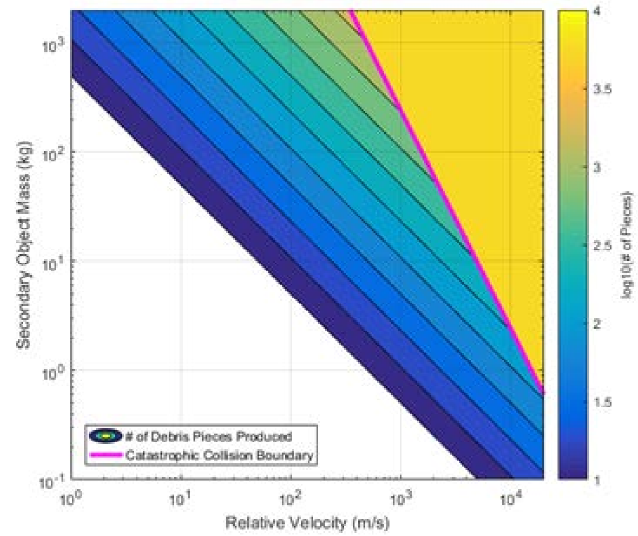
Process Updates and Supporting Analysis

- **HIE Briefing**

HIE Briefing → PowerPoint
Additional plots and data



..input considerations



Fragmentation algorithms developed by the NASA ODPO to assess the debris production potential of any given conjunction.

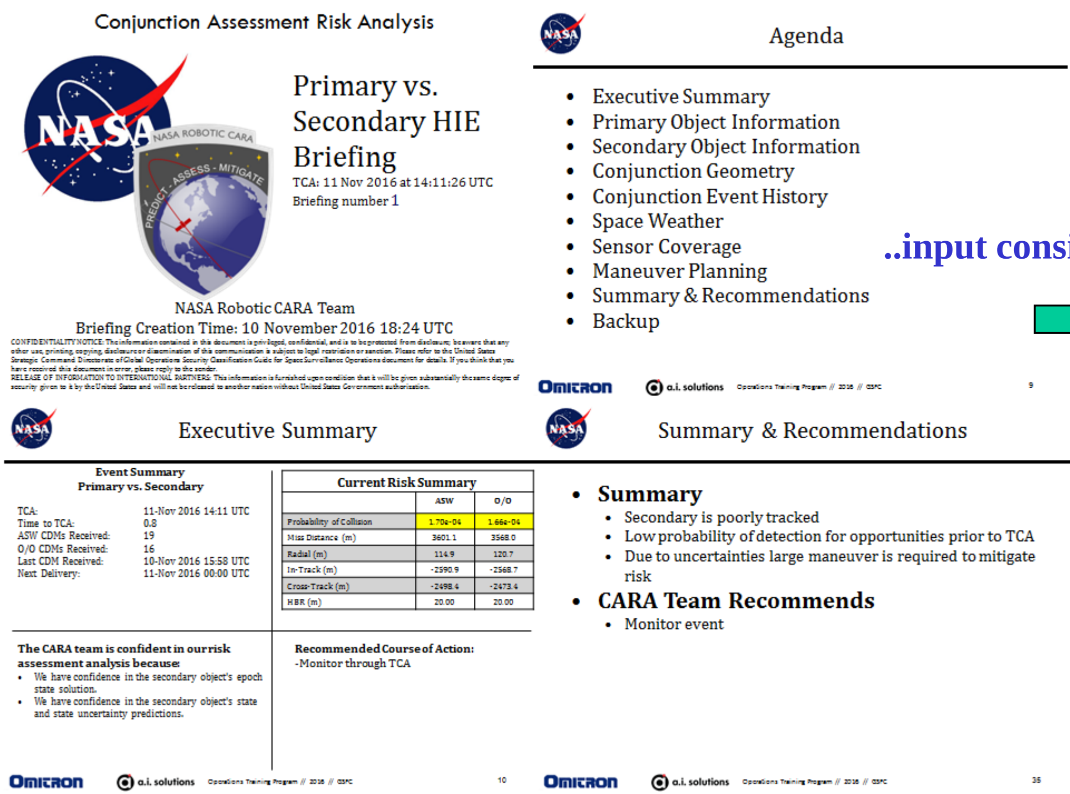
PowerPoint presentation sample deck of an HIE Briefing that provides technical input for decision making.

Process Update:
(4) Collision Consequence for Pc threshold recommendations

Process Updates and Supporting Analysis

- **HIE Briefing**

HIE Briefing → PowerPoint
Additional plots and data



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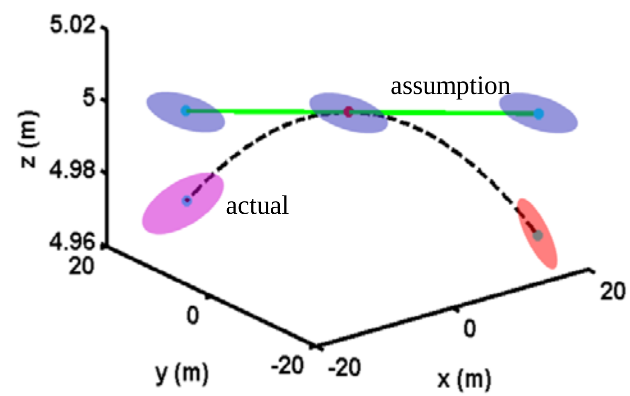


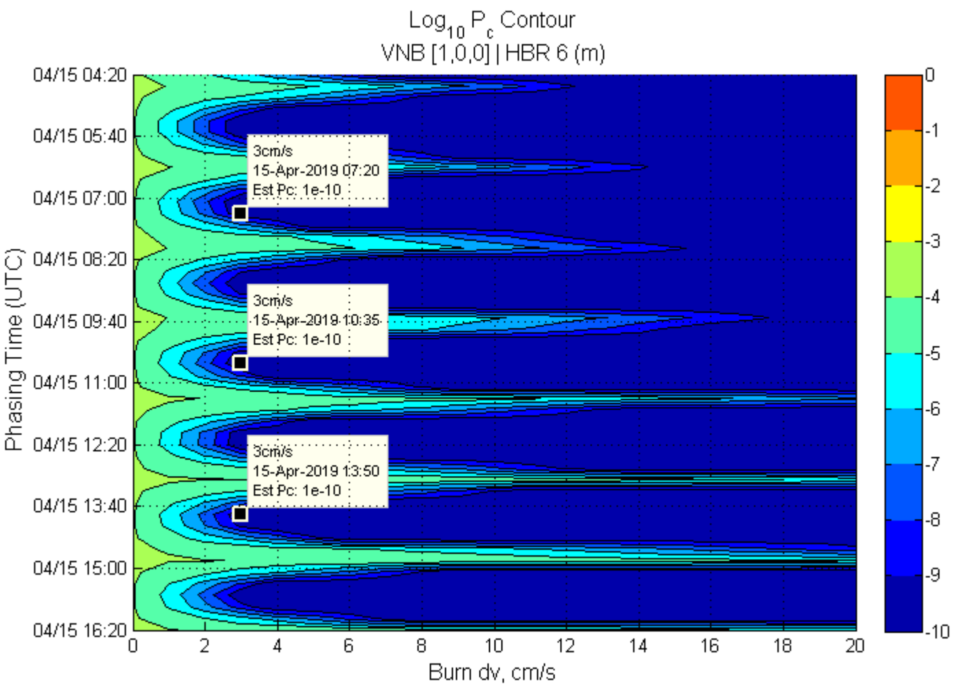
Multivariate Normality (MVN) assumption can be flawed

Process Update:
(5) Multi Variate Normal (Gaussian) evaluation of Cartesian-Framed Covariances

Process Updates and Supporting Analysis

- **Maneuver Trade Space**

Maneuver Trade Space (MTS) → Potential Maneuver Times and Sizes



CARA's recommended post-maneuver Pc remediation is set to 1×10^{-10} ; conservative based on previous analysis

Recommended maneuver times and sizes are highlighted by the CARA Operator. Alternate time ranges and/or maneuver directions can be provided at mission request.

Process Update:
(6) Determining appropriate Pc remediation thresholds

Process Updates and Supporting Analysis

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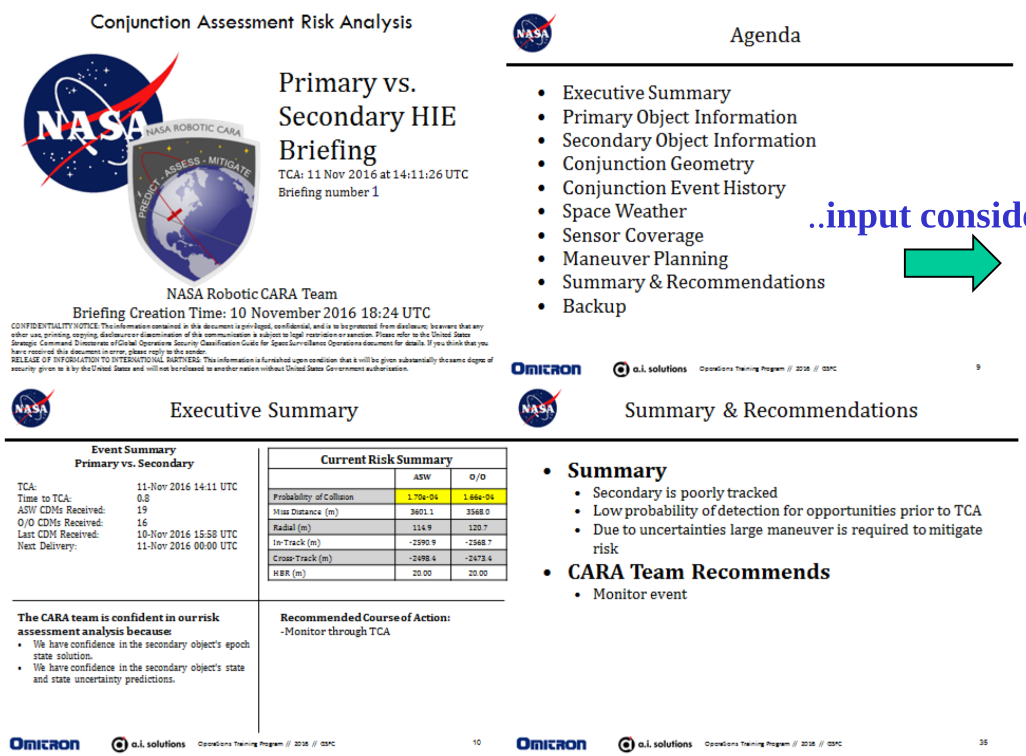
HIE Briefing → PowerPoint
Additional plots and data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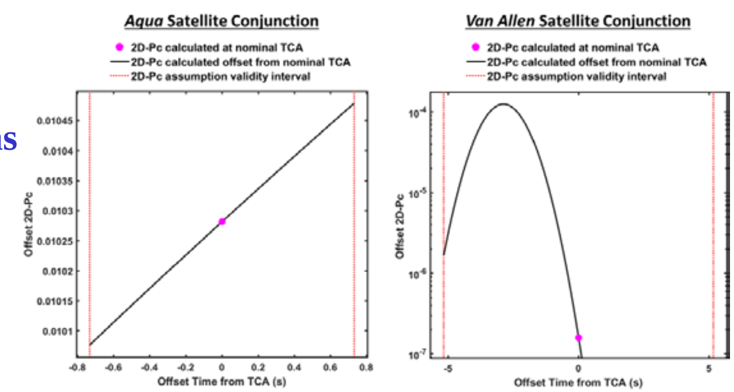

2D Pc assumptions may not apply for some edge cases

Process Update:
(7) 2D Pc Boundaries implementation recommendations and usage

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Devolution

- **Devolution:** **the operations portion of CARA could be pushed out to the mission flight operation teams as an option.**
  - Pending completion of 2 pilot programs over the course of the next 2 years
- **CARA will still remain the CA technical authority under the NASA Office of the Chief Engineer as well as provide CA operations for non-devolving missions**
- **CARA will evaluate 3rd party tools to determine whether they meet the Agency's CA needs.**
  - A tool certification plan identifies the essential ✔ and enhancing ✚ tool features
  - Benchmark test cases are available for each item on the list (list will evolve over time as new capabilities emerge)

Item	Tool Feature	Topical Area	Maneuverable Spacecraft Requirement	Non-Maneuverable Spacecraft Requirement
Point Estimate of Risk	T-1.1	Miss-Distance Reporting	✔	✔
	T-1.2	2-D Pc Calculation from ASW data	✔	✔
	T-1.3	Identify and flag when 2-D Pc Calculation from ASW data is Non-Positive Definite	✔	✔
	T-1.4	2-D Pc Calculation from ASW data with Covariance Cross-Correlation	✚	✚
	T-1.5	Indication of 2-D assumption inadequacy	✔	✔
	T-1.6	Owner/Operator Ephemeris/Pc Calculation	✔ (HEO,GEO), ✚ (LEO)	✔
	T-1.7	Identify and flag Missing Covariance for Pc Calculation	✔ (or T-1.8)	✔ (or T-1.8)
	T-1.8	Covariance Synthesis Capability	✔ (or T-1.7)	✔ (or T-1.7)
	T-1.9	Monte Carlo from TCA: equinoctial frame	✔ (or T-1.10)	✔ (or T-1.10)
	T-1.10	Position Monte Carlo from Epoch	✔ (GEO)	✔ (GEO)
	T-1.11	Collision Consequence	✚	✚
Pc Error Analysis	T-2.1	Covariance mis-sizing sensitivity	✚ (or T-2.2)	✚ (or T-2.2)
	T-2.2	Pc Uncertainty: Full consideration of all error sources	✚	✚
Predicted Situation at Decision Point	T-3.1	Historical Pc Trending (Event Histories)	✚	✔
	T-3.2	Space Weather Sensitivity	✚	✚
	T-3.3	Tracking Prediction	✚	✚
	T-3.4	Predictive Pc Trending	✚	✚
Maneuver Planning Aids	T-4.1	MTS: Single Conjunction	N/A	✔
	T-4.2	MTS: Multiple Conjunctions	N/A	✔
	T-4.3	Maneuver Trade-Space: Execution Error	N/A	✚
Stress Loading	T-5.1	Loading Performance Test	✔	✔

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Conclusions

- **CA field is relatively new and so is constantly evolving**
  - Data sources moving from exclusive DoD-control to commercial availability
  - Space Fence implementation adds smaller objects to catalog
  - Anticipated large constellations will add congestion in certain orbits
    - Use of electric propulsion in large constellations as missions are inserted and deorbited cause additional complication for CA due to inability to do non-cooperative tracking
- **CARA performing extensive R&D to develop more robust algorithms to handle this evolution to handle the various technical challenges**
- **NASA plans to continue to evolve our CA process: improving operations, streamlining approaches, and collaborating with other operators to make the most of limited resources.**

CARA process updates Special Session Presentation

A. Mashiku #AAS-19-702
RECOMMENDED METHODS FOR SETTING MISSION CONJUNCTION ANALYSIS HARD BODY RADII

L. Baars #AAS-612
ASSESSING GEO AND LEO REPEATING CONJUNCTIONS USING HIGH FIDELITY BRUTE FORCE MONTE CARLO SIMULATIONS

M. Hejduk # AAS-652
SATELLITE COLLISION 'PROBABILITY,' 'POSSIBILITY,' AND 'PLAUSIBILITY': A CATEGORIZATION OF COMPETING CA RISK ASSESSMENT PARADIGMS

T. Lechtenberg # AAS-19-669
AN OPERATIONAL ALGORITHM FOR EVALUATING SATELLITE COLLISION CONSEQUENCE

T. Lechtenberg # AAS-19-671
MULTIVARIATE NORMALITY OF CARTESIAN-FRAMED COVARIANCES: EVALUATION AND OPERATIONAL SIGNIFICANCE

D. Hall # AAS-631
DETERMINING APPROPRIATE RISK REMEDIATION THRESHOLDS FROM EMPIRICAL CONJUNCTION DATA USING SURVIVAL PROBABILITY METHODS

D. Hall # AAS-632
IMPLEMENTATION RECOMMENDATIONS AND USAGE BOUNDARIES FOR THE TWO-DIMENSIONAL PROBABILITY OF COLLISION CALCULATION