NASA CARA Prelaunch Analysis and Process

SSA Operators' Workshop
15 May 2024

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Conjunction Assessment Risk Analysis

CARA is an Agency-level resource that protects the orbital environment from collisions between NASA non-HSF missions and other tracked on-orbit objects.

- ~70 on orbit missions
- ~30 mission prelaunch

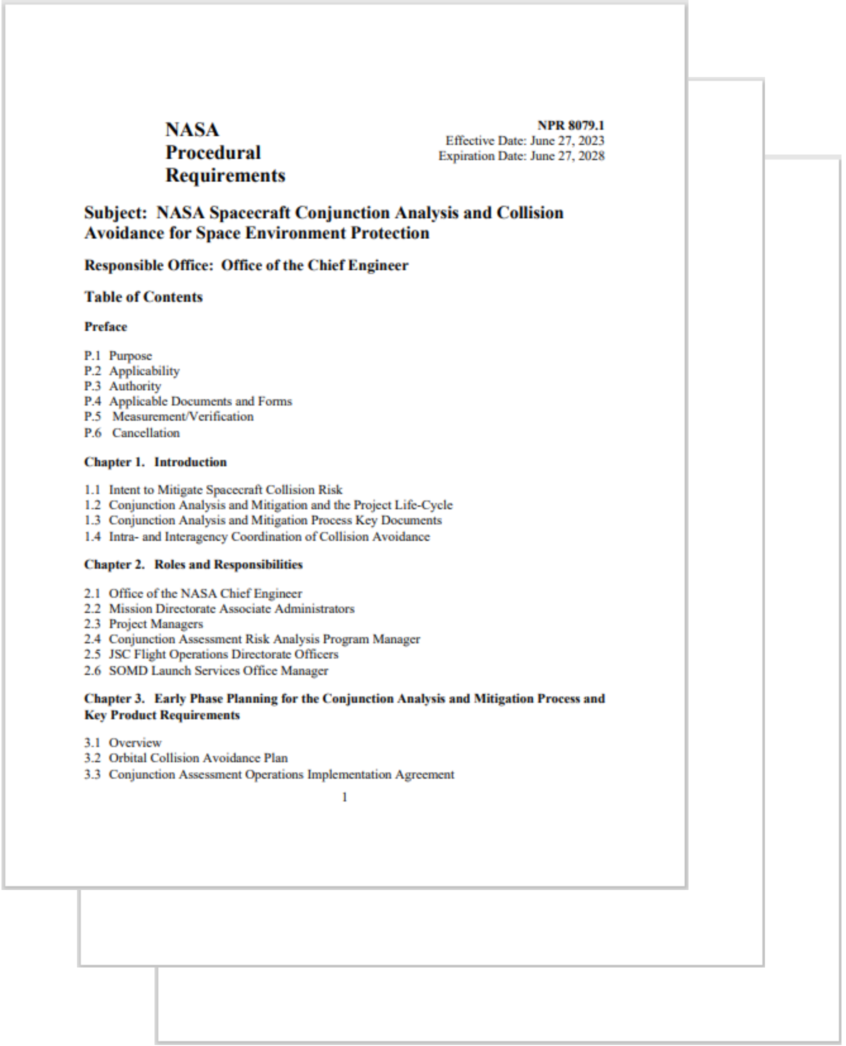
CARA Statement of Purpose:

To take prudent measures, at reasonable cost, to enhance safety of flight, without placing an undue burden on mission operations.

CARA strives to utilize our expertise in conjunction assessment to help missions make informed decisions during their design and conops development.

Objective: provide the conjunction assessment community with the current method that NASA uses to protect our assets and the space environment.

NASA Procedural Requirement (NPR) 8079.1



NASA
Procedural
Requirements

NPR 8079.1
Effective Date: June 27, 2023
Expiration Date: June 27, 2028

Subject: NASA Spacecraft Conjunction Analysis and Collision Avoidance for Space Environment Protection

Responsible Office: Office of the Chief Engineer

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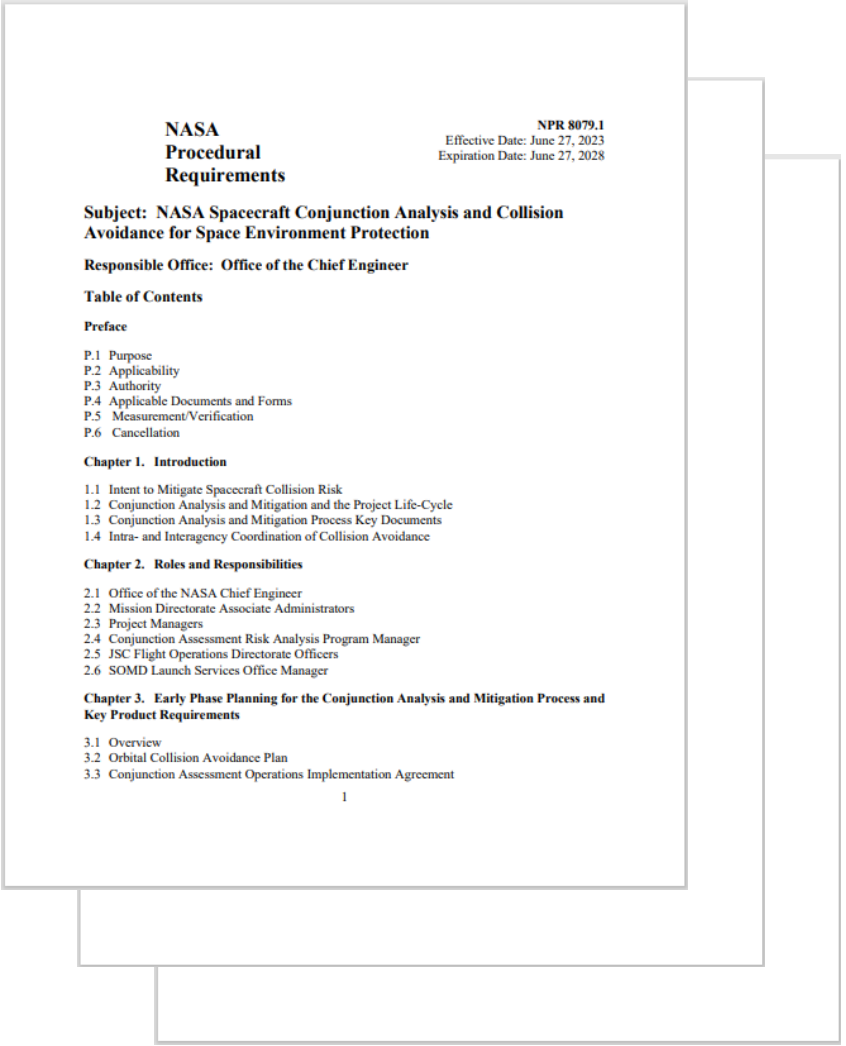
NPR Goal

Protect the space environment and reduce the risk of collision to an acceptable level by establishing the minimum collision avoidance requirements and associated operational protocols for NASA.

NASA Procedural Requirement (NPR) 8079.1



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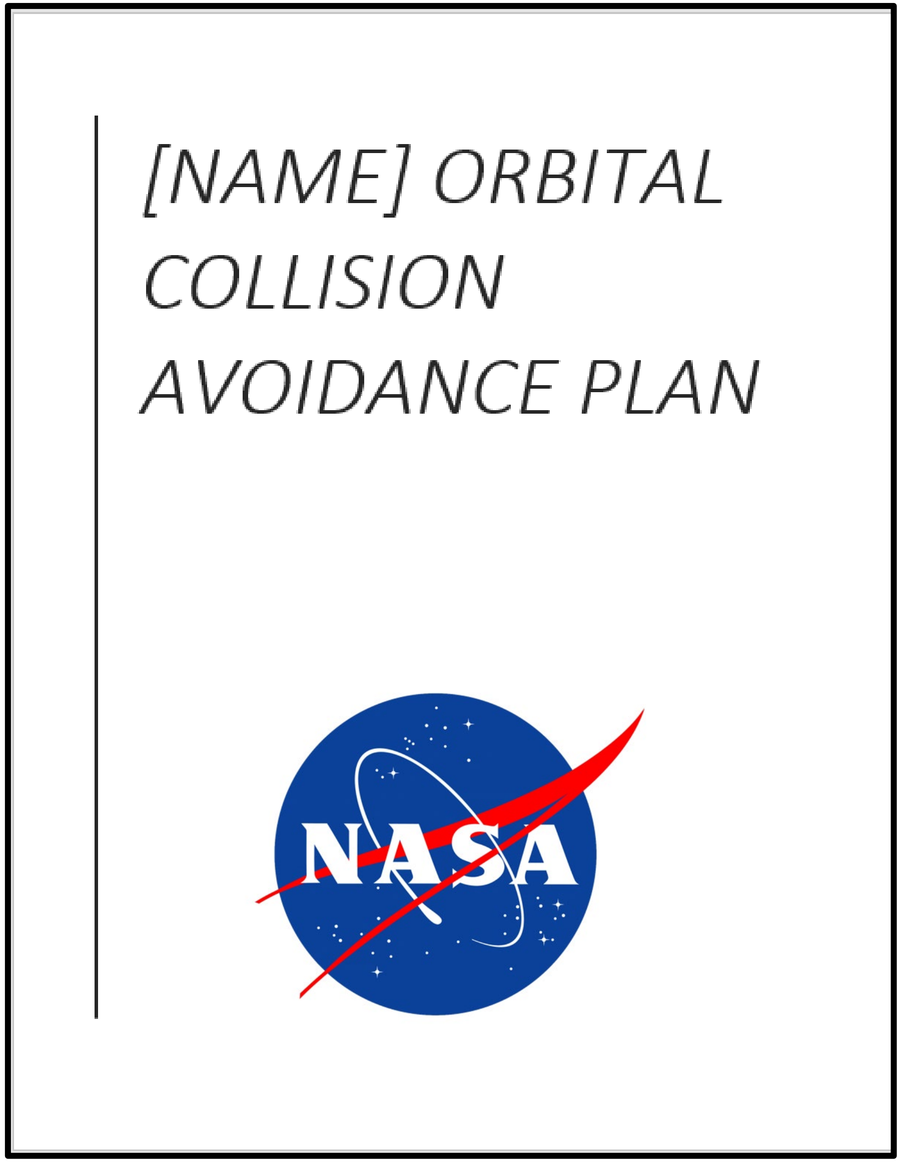
<u>This goal is accomplished by:</u>

Two-fold approach to analyze the satellite design process with **conjunction assessment** and **risk mitigation** in mind, during the **pre-launch process**.

1. Orbital Collision Avoidance Plan
2. Conjunction Assessment Operations Implementation Agreement

NASA Procedural Requirement (NPR) 8079.1


[NAME] ORBITAL COLLISION AVOIDANCE PLAN

Orbital Collision Avoidance Plan (OCAP):

Detailed study and analysis of various mission design parameters and conops related to conjunction assessment and mitigation.

OCAP Requirement & Timeline

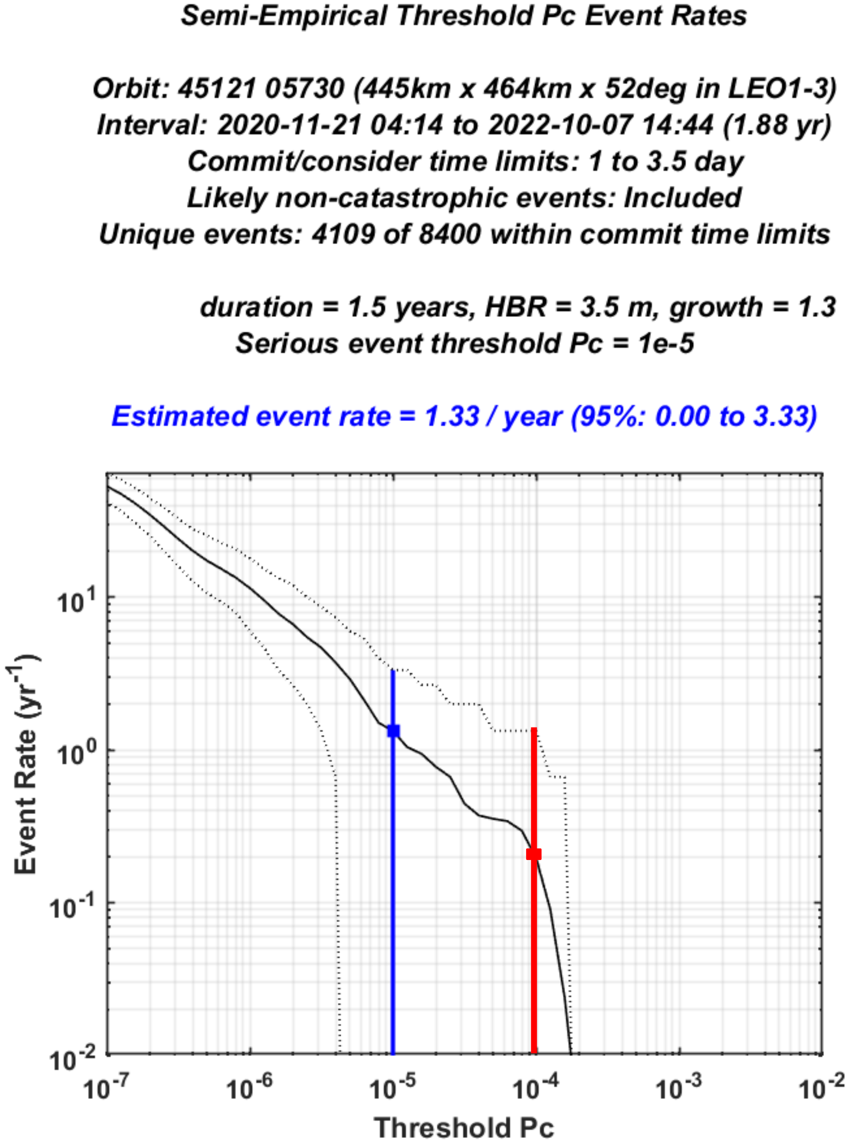
- **NASA Procedural Requirement (NPR) 8079.1**
  - –Requires signed OCAP and compliance matrix document at PDR/Project Approval
  - –Start working with CARA in Pre-Formulation/Formulation Phase
  - –OCAP is completed iteratively and signed by mission and CARA
    - Documents the structured study of aspects of mission design that affect close approach prediction and mitigation during mission operations

Objective: To ensure that all needed conjunction assessment (CA) components are in place when the mission is put into operation

Life-Cycle Phase	Pre-Formulation	Formulation	
7120.5 Life-Cycle Gates	MCR ①	SRR ② SDR	PDR ③
	Notes: ① Project provides initial inputs for OCAP ② Iteration of OCAP content with CARA or JSC FOD ③ Achieve OCAP concurrence (Baseline)		
Conjunction Assessment Products		① Initial OCAP inputs (required)	② Baseline OCAP (required)
NPR-Related Activities	• As concepts develop, project manager coordinates with CARA (non-HSF) or JSC FOD (HSF) for orbit selection options	• Project manager demonstrates application of this NPR • Project manager provides initial OCAP inputs to CARA/JSC FOD review • CARA/JSC FOD begins OCAP analyses	• Project manager baselines OCAP and provides OCAP to CARA/JSC FOD for review and concurrence and subsequent final approval by the program manager

7120.5 Timeline

OCAP Analysis – Event Rate



EventRate Output

- Estimate of the annual rate of events that will rise above a certain Pc threshold.
- Blue line illustrates the 5-95 percentile uncertainty range for a of Pc of 1E-5.
  - ~0 to 3.33 events/year
- Red line illustrates the 5-95 percentile uncertainty range for a Pc of 1E-4 (CARA red threshold).
  - ~0 to 1.05 event/year

NASA Procedural Requirement (NPR) 8079.1

REV 4: Jan 4, 2024

CONJUNCTION ASSESSMENT RISK ANALYSIS ORBITAL CONJUNCTION ASSESSMENT PLAN (OCAP) SCREENING FORM

PROJECT INFORMATION

1. PROJECT NAME:	2. PROJECT POINT OF CONTACT *(Name and title)*:
3. PDR & LAUNCH DATES *(Best current estimates)*:	4. PROJECT POC EMAIL ADDRESS:
PDR: Launch:	

5. SCREENING QUESTIONS

QUESTION NUMBER	SCREENING QUESTION	PROJECT RESPONSE (a) YES	NO
1	Is your spacecraft larger than 10cm per side for LEO or 50cm/side for MEO/HEO/GEO?		
2	Does your spacecraft have a propulsion system? If yes, check one: ☐chemical ☐ electric ☐other		
3	For spacecraft without a propulsion system, are you intentionally performing actions that will change the spacecraft orbit (e.g., differential drag, ...)		
4	Is your spacecraft using a tether?		
5	Are there multiple spacecraft as part of your mission?		
6	Is your spacecraft deploying any child objects?		
7	Is your spacecraft a rideshare?		
8	Will ephemeris with covariance (including any planned maneuvers) be provided based on a mission tracking data source?		
9	Does your spacecraft perform autonomous maneuvering?		
10	Specify the mission orbit apogee ☐ perigee ☐ inclination ☐ If different than the mission orbit, specify the injection apogee ☐ perigee ☐ inclination ☐		

6. PROJECT CERTIFICATION*

– For Office Use Only –

**Sign only if no further analyses are needed and this form will serve as the OCAP.*

By signing below, I certify that the above information is an accurate representation of the project architecture and that CARA has agreed that this form is sufficient to serve as the OCAP for this mission.

a. PROJECT APPROVER *(Name and title)*:	b. SIGNATURE	c. DATE

7. OCAP COMPLETION RECOMMENDATION

(To be completed by CARA Representative)

Based on the information provided, CARA makes the following recommendation:

CLASSIFICATION (SELECT ONE) (a)	RISK CLASSIFICATION RECOMMENDATION (b)
☐	This project meets the criteria to utilize this form as OCAP. No further analysis is recommended unless future changes to the project would change the response to one of the screening questions.
☐	The project does not meet all of the criteria required to utilize this form as the OCAP; a tailored OCAP is required.
☐	The project screening criteria answers justify completion of a full OCAP.

c. CARA COMMENTS:

d. CARA REPRESENTATIVE (Name and title):	e. SIGNATURE	f. DATE

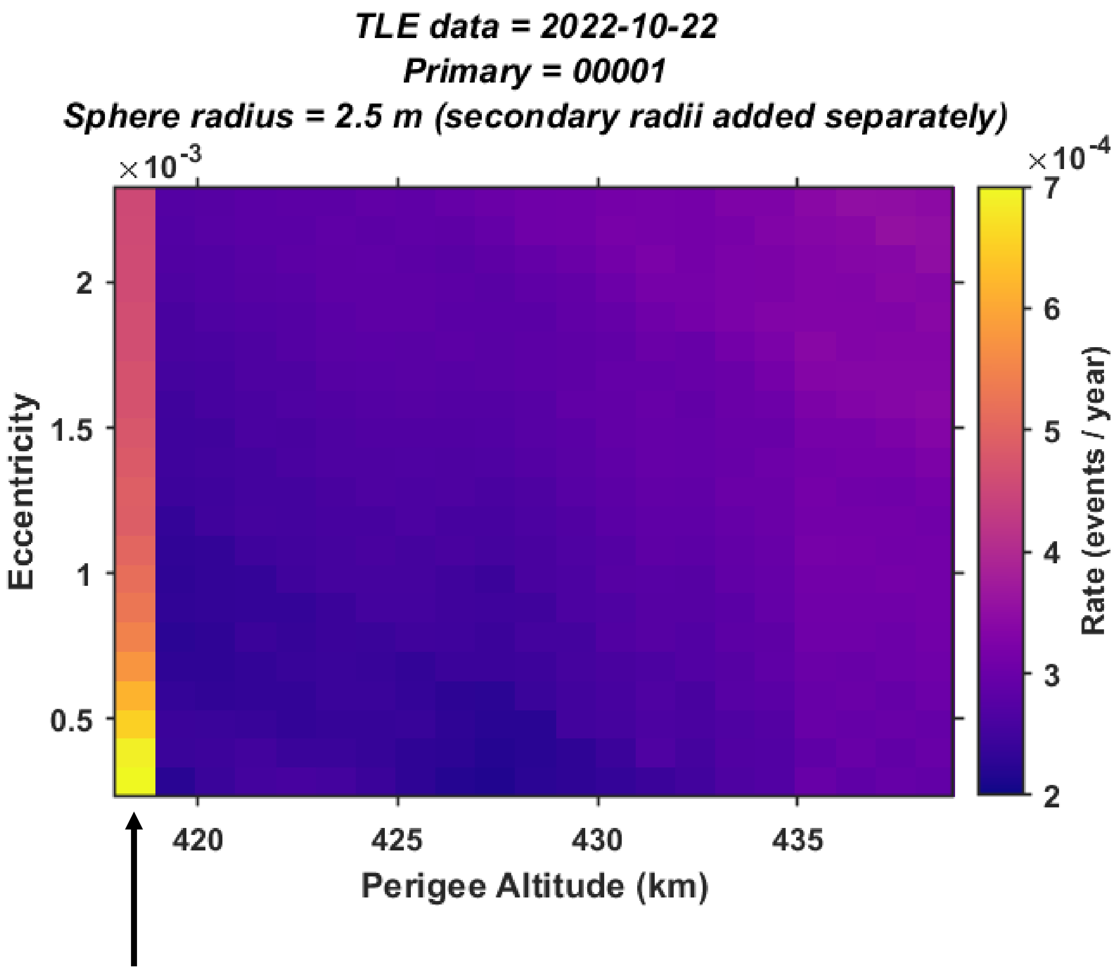
OCAP Screening Process

- –Spacecraft size
- –Propulsion type
- –Use of tethers
- –Number of spacecrafts in mission
- –Deployment of child objects
- –Rideshare
- –Ephemeris with covariance
- –Autonomous maneuvering
- –Orbit apogee, perigee, and inclination

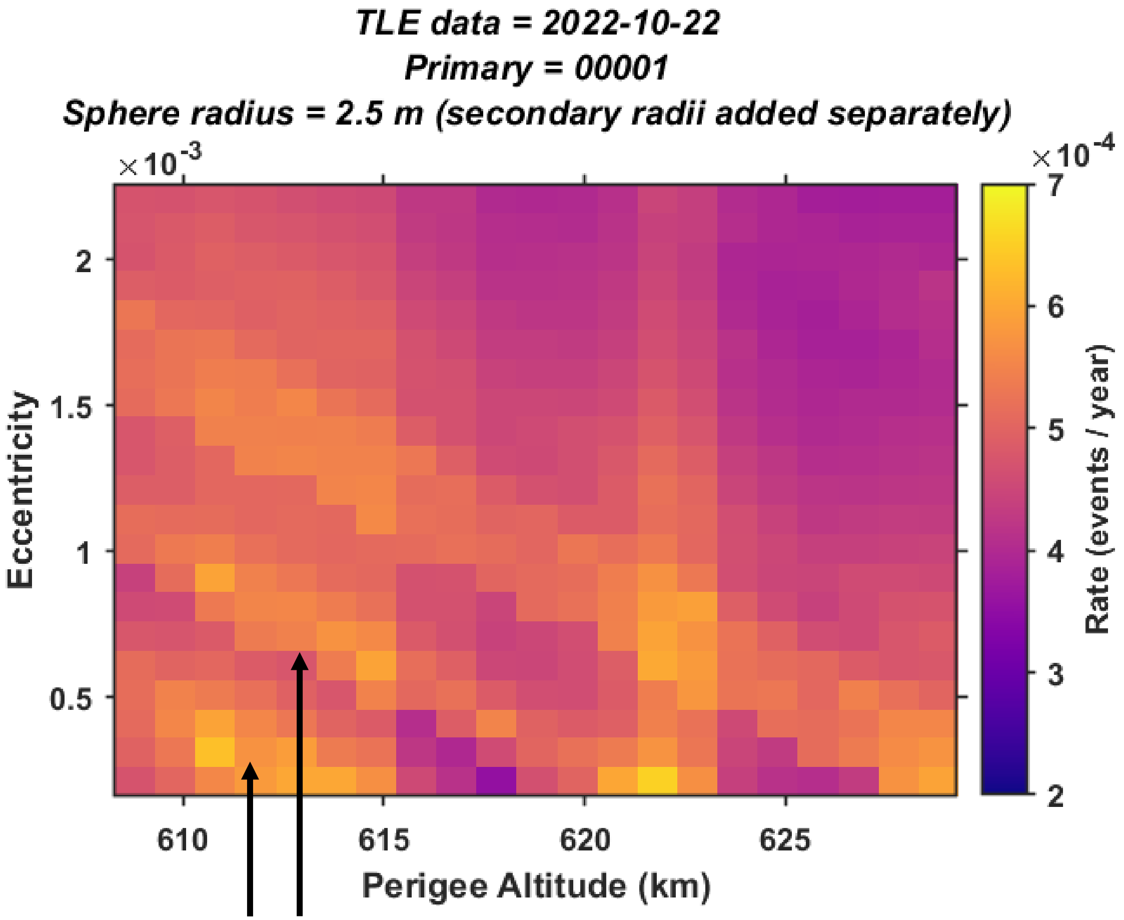
OCAP Analysis

- **Orbit Selection & Placement**
  - CARA analyzes colocation, transit burden, high interest event (HIE) rate
  - Potential to influence orbit selection and transit CONOP
- **Deployment, Cataloging, Trackability**
  - CARA analyzes these aspects for conjunction assessment (CA) risk
  - Potential to influence strategy for multiple payload deployment, initial orbit determination after launch, tracking enhancements
- **Spacecraft Operations**
  - Ephemeris with covariance generation: orbit determination (OD) source & setup, covariance realism, maneuver modeling
  - Conjunction Mitigation Options (e.g., thrusters, differential drag, attitude slews)
  - Autonomous Maneuvering
- **Risk Assessment Parameters (Hard Body Radius)**

OCAP Analysis – Risk Heatmaps



band of high risk due to ISS (~418 km)

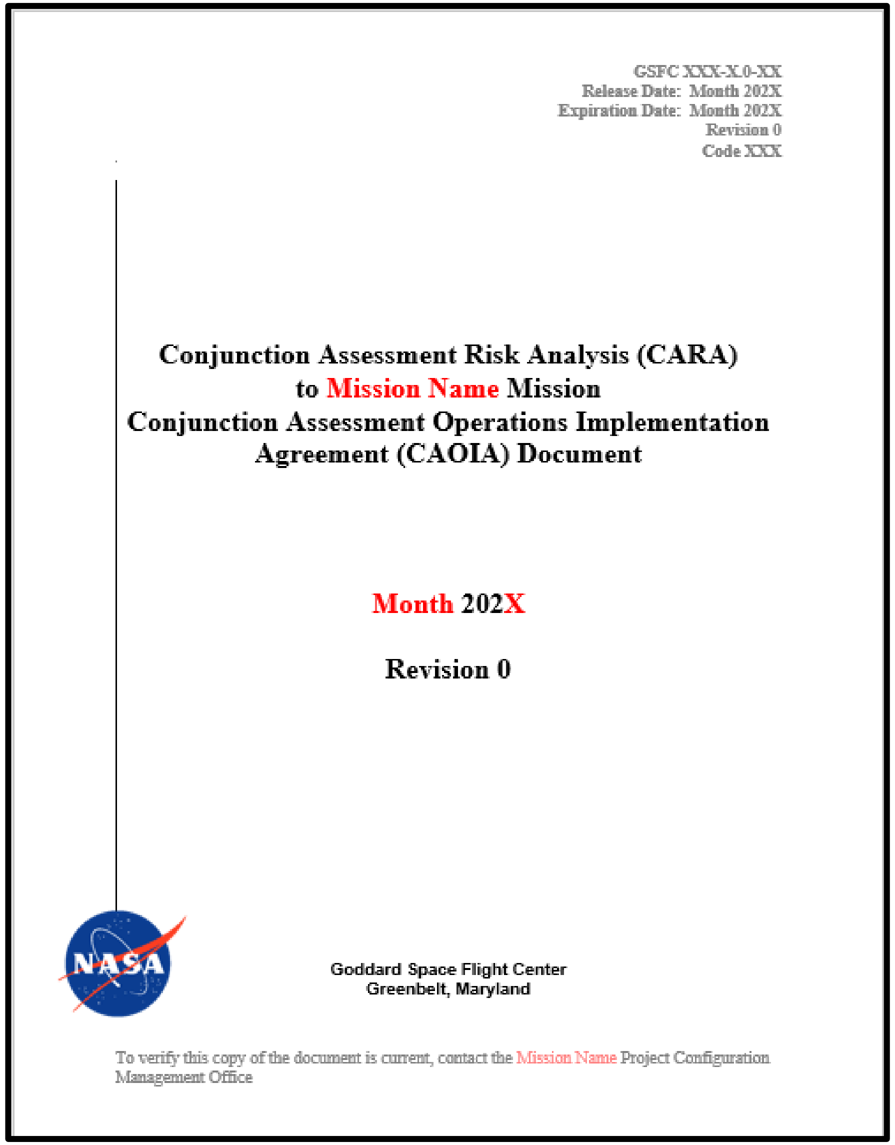


- diagonal bands of higher risk
- risk is highest when the perigee/apogee of two satellites overlap

CARA Recommendations & Signature

- **Each analysis section includes:**
  - *CARA Recommendations* to summarize any CARA concerns with current design and recommendations for addressing them
  - *Mission Response* to document how the project intends to address the concerns highlighted by CARA
- **Agreement between the mission and CARA on these items is required for signature**
  - CARA has authority to tailor NPR 8079.1 requirements when necessary
- **Knowing which OCAP analyses are relevant to a mission, even if they can't yet be performed, allows mission to insert requirements into contract request for proposals (RFPs) to ensure final design meets NPR 8079.1**

NASA Procedural Requirement (NPR) 8079.1


GSFC XXX-X.0-XX
Release Date: Month 202X
Expiration Date: Month 202X
Revision 0
Code XXX

Conjunction Assessment Risk Analysis (CARA)
to Mission Name Mission
Conjunction Assessment Operations Implementation
Agreement (CAOIA) Document

Month 202X

Revision 0

Goddard Space Flight Center
Greenbelt, Maryland

To verify this copy of the document is current, contact the Mission Name Project Configuration Management Office

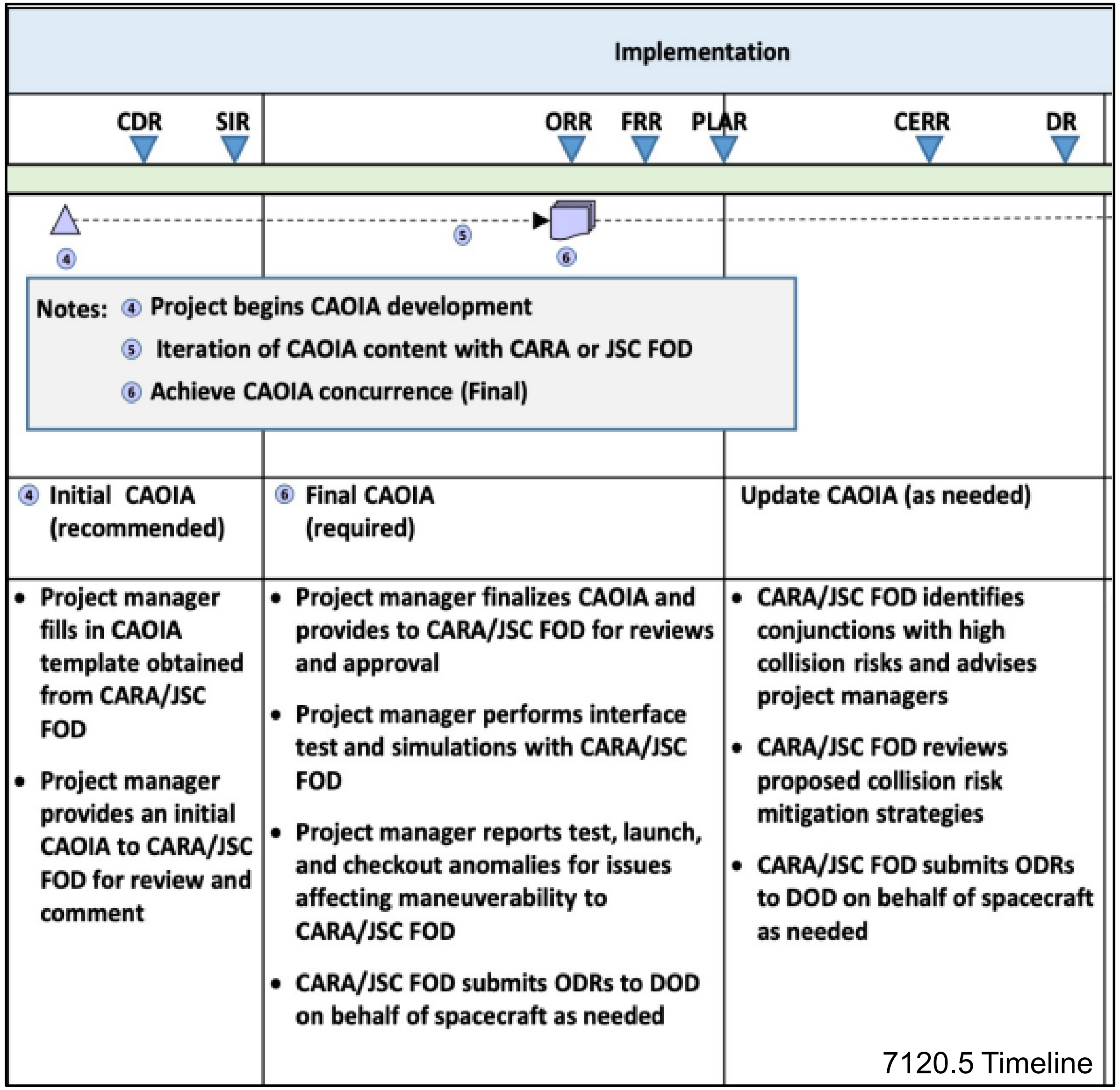
Conjunction Assessment Operations Implementation Agreement (CAOIA):

Agreement between missions and CARA documenting the specific operational processes the project plans to implement to protect the spacecraft and space environment.

CAOIA Requirement & Timeline

- **NASA Procedural Requirement (NPR) 8079.1**
  - Requires completion by ORR/ORR equivalent
  - Start working with CARA in the Implementation phase
  - CAOIA is completed iteratively, and can be updated as needed by the missions

Objective: To ensure that all necessary operational processes are in place prior to launch.



CAOIA Contents – Mission Ops Overview

- **Mission Operations Overview**
  - –Mission orbit determination (OD), ephemeris, and covariance generation
  - –Mission launch and transfer orbit philosophy
  - –Nominal orbit and orbit maintenance philosophy
  - –End of mission planning
  - –Spacecraft anomaly support and products
  - –Hard Body Radius (HBR) and spacecraft mass calculations and usage

CAOIA Contents – Screening Process

CARA Responsibilities
• Provide routine screening results • Provide off-nominal maneuver screening • Perform manual OD on secondary objects • Determine secondary OD actionability • Perform analysis of secondary object tasking • Provide routine & high interest event analysis • Provide recommendations to Mission

- **Launch, early orbit, and end-of-mission CA screenings**
  - –Space Act Agreement with SpaceX
- **Nominal orbit CA screening**
- **HIE CA screenings and support**
  - –HIE actionability
  - –HIE secondary O/O contact
- **CA screening volumes and Pc threshold**
  - –Monitor volume
  - –Tasks volume

CA: Conjunction Assessment, HIE: High Interest Event, OD: Orbit Determination, O/O: Owner/Operator, Pc: Probability of Collision

CAOIA Contents – Deliverables

- **Mission Deliverables to CARA Team**
  - –Mission data products
  - –Data product transfer – mission to CARA
  - –Ephemeris delivery frequency and duration
  - –Simulation requests
- **CARA Deliverables to Mission**
  - –CARA Team data products
  - –Security Requirements to receive CARA Team data products
  - –Data product transfer – CARA to mission
  - –Conjunction assessment screening summary results
  - –High-Interest Event Summaries
  - –Maneuver Screening Analysis Reports

CAOIA Contents – Simulation Support

General Simulation Information

Name of Mission:	
Name of Mission Sim:	
Mission Sim coordinator(s):	
Length of Mission Sim:	
Mission Sim Calendar Dates/Times:	
Mission Sim Wall Clock Dates/Times (if different than Calendar dates/times):	
Time of Closest Approach (TCA) for requested event:	
Date(s) Required for Real-Time CARA Operator (if applicable)	

Real-time CARA Operator Support (check all that apply)

CA Summary Report Real Time Delivery (Reports will be sent at nominal screening times)	
HIE Briefing (CARA operator presents in Teams meeting)	
On Call (for questions)	
Product Only Support (No real time support requested)	
Other	

Requested Products (check all that apply)

Product Name	**Description**	**Requested for Sim**
CA Summary Report	This report is typically delivered 3 times per day for LEO screenings. There can be changes because space weather is updated prior to each screening. Any updated tracking would be reflected in these reports.	
MTS (Maneuver Trade Space)	Helps provide RMM (Risk Mitigation Maneuver) times and delta-Vs. This is typically provided to missions around 3 days prior to TCA (time of closest approach)	
HIE (High Interest Event) Package	Package is a powerpoint presentation which contains information about the primary and secondary objects, conjunction geometry etc.	

Simulation Support

– CARA can support three full simulations or operations readiness test (ORT) for missions

– Each simulation is tailored to missions unique and specific needs

– The simulation can be as simple or complex as needed:

- Summary Reports with green events to confirm listserv operation and become familiar with the reports
- Full scale High Interest Event (HIE) with Maneuver Tradespace (MTS), Maneuver Screening (MSA), and a HIE briefing

CAOIA Contents – Emergency Maneuvers

Emergency Maneuver Capabilities Form

Section		
1	Name of Mission	
2	Mission SATCAT ID	XXXXX
3	Attitude Adjustment/Slew Capability	Y/N
3a	If Y for 3, Maximum HBR value (m)	
3b	If Y for 3, Minimum HBR value (m)	
3c	If Y for 3, Additional HBR states (m)	
3d	Minimum time needed for slew planning, command & execution (hours) wrt TCA	
4	Chemical/Propulsive Risk Mitigating Maneuver (RMM) Capability	Y/N
4a	Minimum time needed for RMM planning, command & execution (hours) wrt TCA	
5	Differential Drag RMM Capability	Y/N
5a	If Y for 5, Maximum Ballistic Coefficient	
5b	If Y for 5, Minimum Ballistic Coefficient	
5c	Minimum time needed for differential drag planning, command & execution (hours) wrt TCA	
6	Electric Propulsion Capability	Y/N
6a	Minimum time needed for electric propulsion planning, command & execution (hours) wrt TCA	
7	Other spacecraft operational constraints (i.e., Attitude pointing requirements, Eclipse conditions, Attitude Control System limitations etc.)	

- CARA is in the process of establishing emergency procedures for extraordinarily high-risk events. The aim is to have all spacecraft capabilities and limitations documented in advance.
- CARA is soliciting all relevant information on maneuverability, attitude adjustment, and slew capabilities to establish mission-specific tailored support for emergency events.

CARA – MADCAP Joint Support

JPL D-XXXXX
Release Date: Month 2024
Revision 0

Conjunction Assessment Risk Analysis (CARA) and MADCAP
to XXXX
Conjunction Assessment Operations Implementation Agreement (CAOIA) Document

Month 2024

Revision 0

To verify this copy of the document is current, contact the Mission Name Project

CARA – MADCAP Joint CAOIA

– CARA supports NASA assets in Low Earth Orbit (LEO), Geosynchronous Orbit (GEO), and Earth Gravity Assist (EGAs) for greater than 3 hours
– Multimission Automated Deepspace Conjunction Assessment Process (MADCAP) supports non-Earth orbiting NASA assets
– CARA and MADCAP can provide joint support for mission who require LEO/GEO/EGA and non-Earth orbiting CA screenings

Summary

- **Early engagement in the OCAP and CAOIA process helps:**
  - –ensure that all needed conjunction assessment components are in place when the mission is put into operation
  - –necessary operational processes are in place prior to mission launch
  - –helps missions insert requirements in contract request for proposals
  - –reduce the risk to the space environment

Acronyms

- CA: Conjunction Assessment
- CAOIA: Conjunction Assessment Operations Implementation Agreement
- CARA: Conjunction Assessment Risk Analysis
- COLA: Collision on Launch Assessment
- HBR: Hard-body Radius
- HIE: High Interest Event
- NPR: NASA Procedural Requirements
- OCAP: Orbital Collision Avoidance Plan
- OD: Orbit Determination
- O/O: Owner Operator
- Pc: Probability of Collision
- SSN: Space Surveillance Network

BACKUP

CARA Analyses & Tools

- **Colocation:**
  - LongTermRisk in medium-term mode to catch any temporal peaks
- **HIE Rate:**
  - EventRate to evaluate HIE rate of proposed orbit based on historical HIE rates of CARA fleet in nearby orbits
- **Transit Burden:**
  - Evaluate transit CONOP vs population of altitude bands being crossed
- **Trackability**
  - Assessed based on historical tracking performance of objects with known sizes
- **Mitigation Options**
  - Evaluate maneuver CONOPS or differential drag efficacy
- **Other Evaluations**
  - Compare to best practices

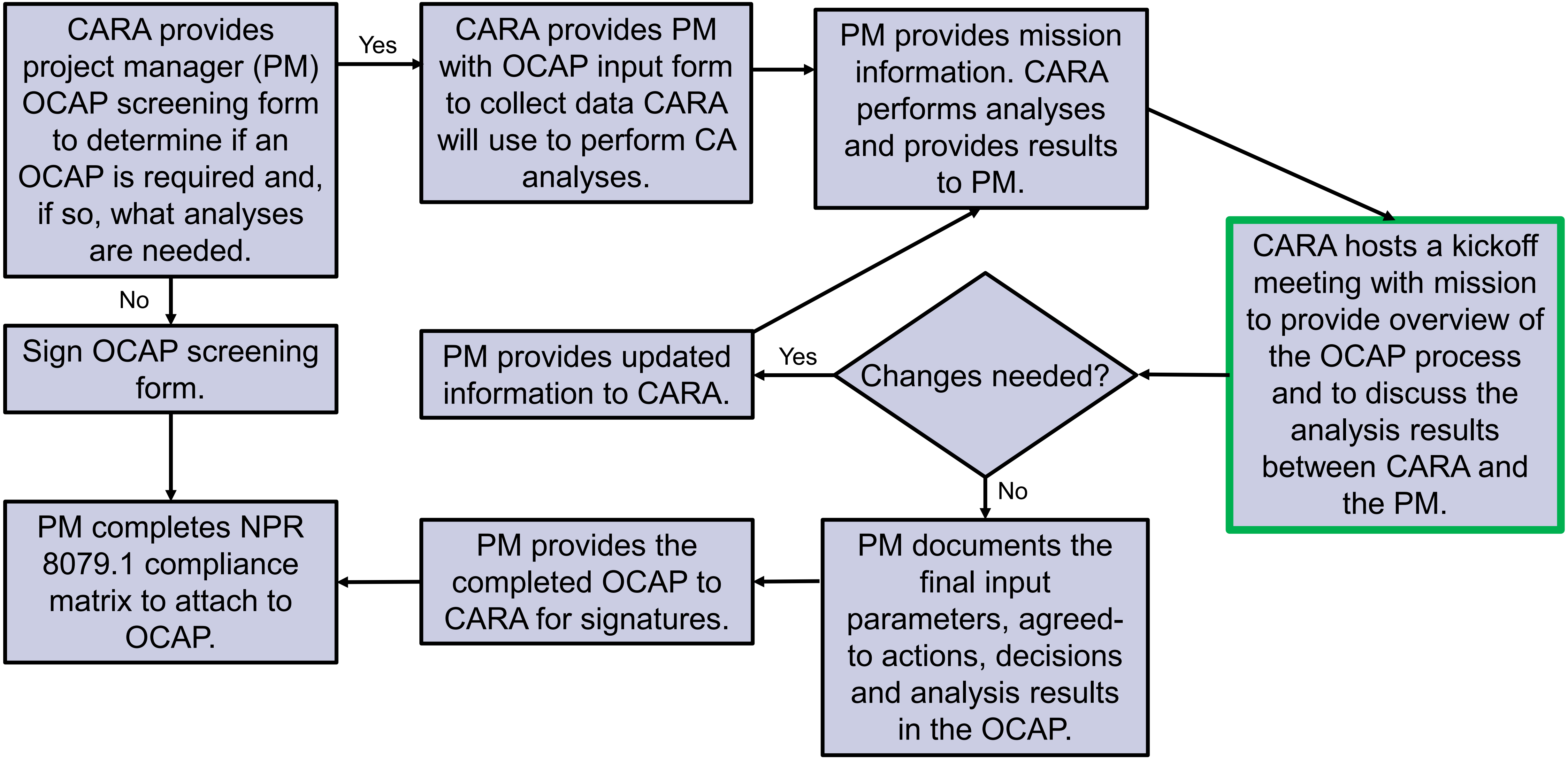
OCAP Requirement & Timeline 7120.8

- **NASA Procedural Requirement (NPR) 8079.1**
  - –Requires signed OCAP and compliance matrix document at Project Approval
  - –Start working with CARA in Formulation Phase
  - –OCAP is completed iteratively and signed by mission and CARA
    - Documents the structured study of aspects of mission design that affect close approach prediction and mitigation during mission operations

Life-Cycle Phase	Pre-Formulation	Formulation	
7120.8 Life-Cycle Gates	ATP	Project Approval ① ② ③ Notes: ① Project provides initial inputs for OCAP ② Iteration of OCAP content with CARA or JSC FOD ③ Achieve OCAP concurrence (Baseline)	CA ④
Conjunction Assessment Products		Preliminary OCAP (recommended) Baseline OCAP (required)	
NPR-Related Activities	• As concepts develop, project manager coordinates with CARA (non-HSF) or JSC FOD (HSF) for orbit selection options	• Project manager demonstrates application of this NPR • Project manager provides initial OCAP inputs to CARA/JSC FOD review • CARA/JSC FOD begins OCAP analyses • Project manager baselines OCAP and provides OCAP to CARA/JSC FOD for review and concurrence and subsequent final approval by the program manager	• Project manage • Project manage • Project manage • Project manage • Project manage maneuverabilit • CARA/JSC FOD • CARA/JSC FOD • CARA/JSC FOD • CARA/JSC FOD • CARA/JSC FOD
Legend	ATP Authority to Proceed into Formulation CA Continuation Assessment CARA Conjunction Assessment Risk Analysis CAOIA Conjunction Assessment Operations Implementation Agre DOD Department of Defense		

Objective: To ensure that all needed CA components are in place when the mission is put into operation

OCAP Development Iterative Process



OCAP Document Contents

1. **Project Overview**
2. **Spacecraft Design**

Mission narrative with context pertinent to CA

3. **Orbit Selection & Placement**
   - CARA analyzes colocation, transit burden, HIE rate
   - Potential to influence orbit selection and transit CONOP
4. **Deployment, Cataloging, Trackability**
   - CARA analyzes these aspects for CA risk
   - Potential to influence strategy for multiple payload deployment, initial orbit determination after launch, tracking enhancements

CARA analysis performed early in mission design process for opportunity to influence CA aspects

5. **Spacecraft Operations**
   - Ephemeris with covariance generation: OD source & setup, covariance realism, maneuver modeling
   - Conjunction Mitigation Options (e.g., thrusters, differential drag, attitude slews)
   - Autonomous Maneuvering
6. **Risk Assessment Parameters (HBR)**

Deployment, Improving Cataloging, and Enhancing Trackability

- ***Deployment*: determine whether the deployment method enables cataloging by the U.S. space surveillance network (SSN)**
  - Parent/child, multiple payload deployment scenarios require planning at design time
  - Recommend adjustments to deployment if assessed to be potentially problematic
- ***Improving Cataloging*: large rideshare launches can require several weeks to be fully cataloged, which delays the on-orbit collision avoidance process for such spacecraft and adds risk for those spacecraft that begin their transit out of the cluster to other orbital locations**
  - Analysis and pre-planning ensure that needed information will be available to the launch cataloging agency if some of the more challenging launch and/or deployment mechanisms are employed
- ***Enhancing Trackability*: determine whether the spacecraft meets the SSN trackability requirements**
  - Recommend trackability enhancements if necessary

Orbit Selection & Placement

- ***Colocation*: determine whether any known or existing spacecraft present a systematic conjunction likelihood with the proposed spacecraft orbit**
  - Recommend slight adjustments to the orbit to obviate systematic conjunctions
  - Or ensure required infrastructure and communications to manage frequent systematic conjunctions
- ***Transit burden*: determine what conjunctions a spacecraft may encounter as it moves from the injection orbit to the mission orbit and from the mission orbit to the disposal orbit**
  - Recommend appropriate active coordination activities and capabilities necessary to accomplish transits safely
  - During ascent and disposal, the expectation is that the transiting spacecraft will yield right-of-way to on-station active spacecraft
- ***Close approach event density*: drawing on historical conjunction database, run tools to estimate the number of conjunctions, high-interest close approach events, and mitigation actions required over the mission's expected lifetime**
  - Provide analysis to mission for refining operations plans, staffing levels, and conjunction remediation approach

Spacecraft Operations

- ***Ephemeris generation*: determine whether the O/O orbit determination approach is adequate for providing O/O predicted ephemerides that can serve as the basis for conjunction assessment decisions**
  - Recommend needed enhancements or upgrades
- ***Conjunction mitigation options*: assess propulsive and/or attitude reorientation options for conjunction remediation**
  - Recommend best approach balancing capability and effectiveness
- ***Autonomous maneuvering*: determine whether the as-designed autonomous maneuver control approach will integrate properly with the collision avoidance paradigm or whether design changes will be necessary**
  - Assess potential risk factors across each aspect of autonomous maneuvering
  - Recommend needed design changes

Risk Assessment Parameters

- ***Hard Body Radius (HBR)*: based on spacecraft dimensions, produce a set of possibilities for a payload HBR value necessary for calculation of probability of collision (Pc)**
  - –Recommend HBR value based on dimensions and known attitude profiles

OCAP Notes

- **If all inputs are not known at time of OCAP preparation, TBDs can be addressed via OCAP update or deferred to the CAOIA as appropriate**
  – OCAP completion as early as possible in the mission design phase allows for efficiency and cost effectiveness
- **Knowing which OCAP analyses are relevant to a mission, even if they can't yet be performed, allows mission to insert requirements into contract RFPs to ensure final design meets NPR 8079.1**

Mission Operations Overview

- Mission orbit determination (OD), ephemeris, and covariance generation
- Mission launch and transfer orbit philosophy
- Nominal orbit and orbit maintenance philosophy
- End of mission planning
- Spacecraft anomaly support and products
- Notification to CARA
- Hard Body Radius (HBR) calculations and usage
- Spacecraft mass calculation and usage

Mission Deliverables to CARA

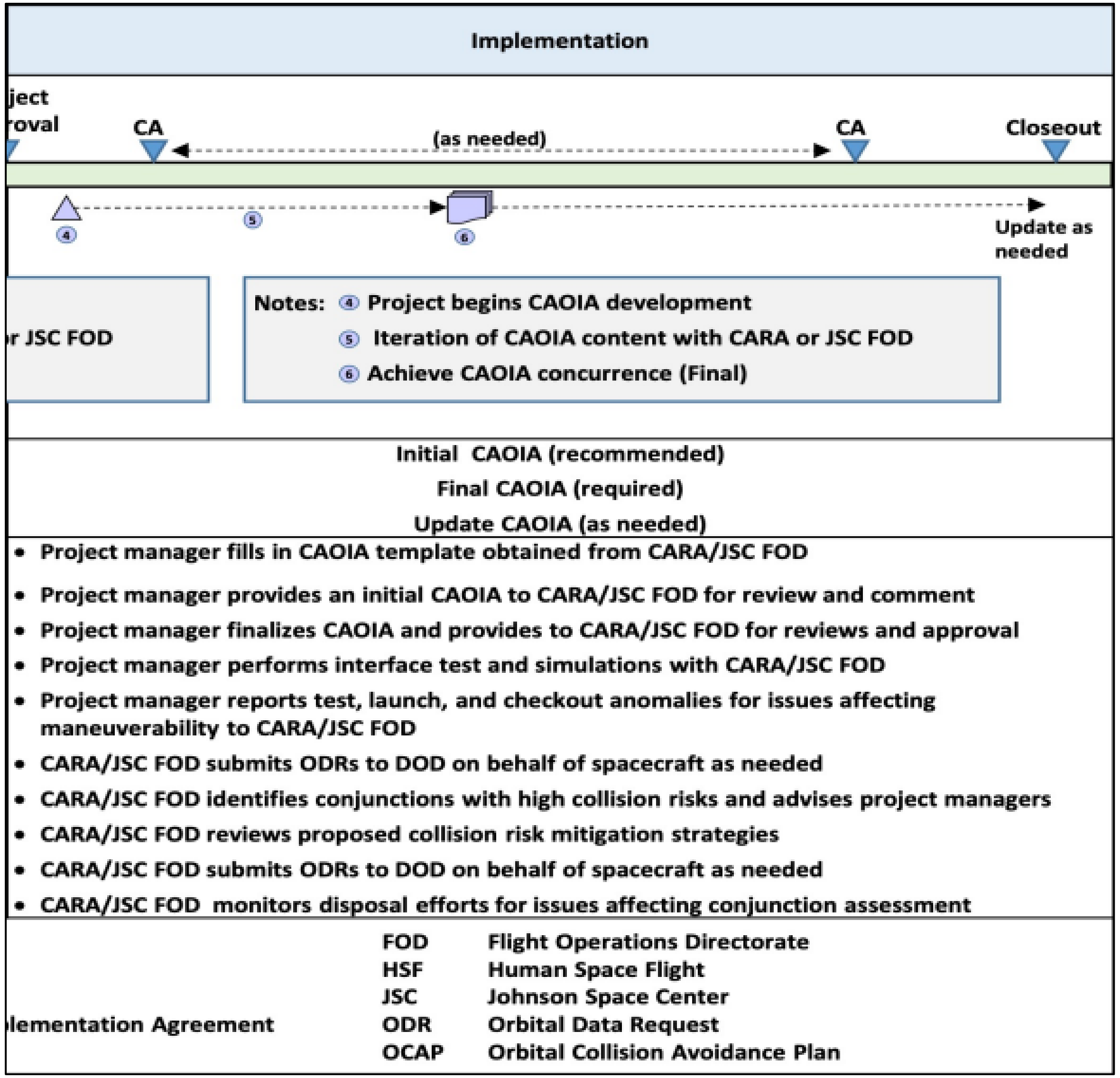
- **Mission data products delivered to CARA**
  - –Data products delivered from mission MOC to CARA
- **Simulation requests**
  - –Testing the interface simulation
  - –Full simulations
- **Ephemeris delivery frequency and duration**
  - –Launch, early orbit, and ascent phase
  - –Mission operations phase
  - –During end-of-mission phase
- **Mission nominal predicted ephemeris and covariance**
- **Mission maneuver related data products**

CARA Deliverables to Mission

- Security requirements to receive CARA data products
- CARA data products to delivered to the Mission
- Conjunction assessment screening summary results
- High Interest Events (HIE) summaries
- Maneuver screening analysis report

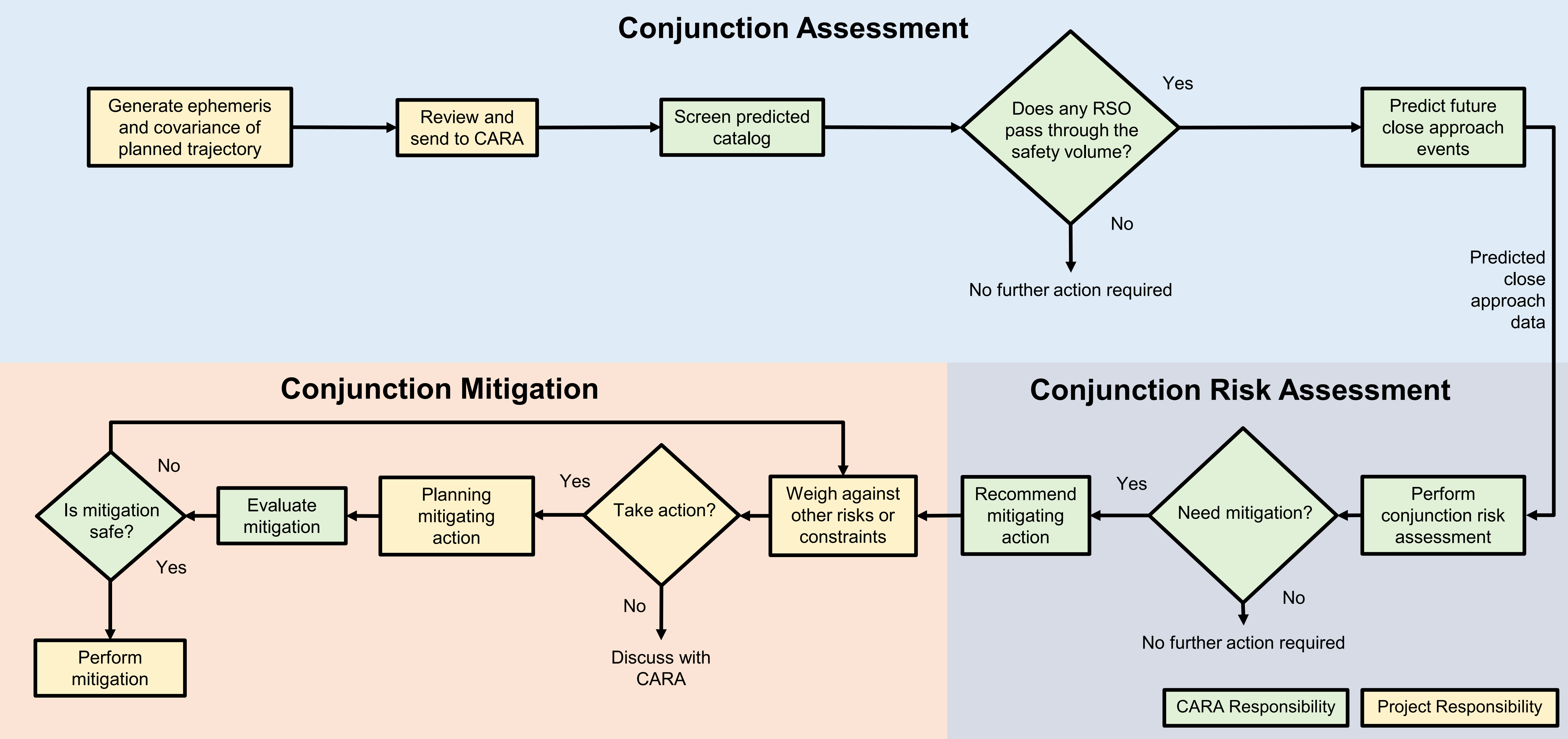
CAOIA Requirement & Timeline 7120.8

- **NASA Procedural Requirement (NPR) 8079.1**
  - –Requires completion by ORR equivalent
  - –Start working with CARA in the Implementation Phase
  - –CAOIA is completed iteratively, and can be updated as needed by the missions



Objective: To ensure that all necessary operational processes are in place prior to launch.

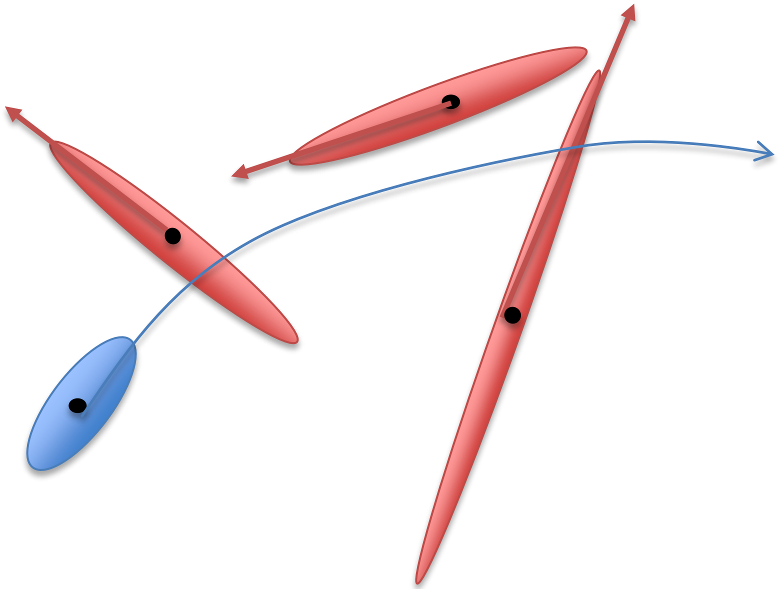
Conjunction Assessment and Mitigation Process



OPERATIONS

CARA Orbital Safety Analysts (OSA)

- The 18 SDS maintains a precision state for all trackable objects
  - Uses non-cooperative tracking from the Space Surveillance Network (SSN); does not account for planned maneuvers
- CARA has a team of dedicated Orbital Safety Analysts (OSAs) located at Vandenberg SFB:
  - Perform routine screenings – 3x day for LEO, 2x for GEO/HEO
    - Against 18th's precision solution for the primary and against O/O-provided ephemerides
  - Inspect automated orbit determination for secondaries
  - Perform manual orbit determination, if warranted
  - Generate and deliver necessary data products
- OSA positions staffed 20 hours/day – *will be 24x7 in FY24*

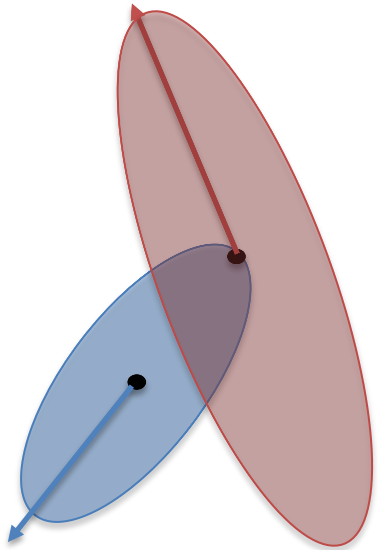


The **Screening Duration** is the "lookout" period of time for which conjunctions are identified. This is presently 7 days for LEO assets and 10 days for GEO/HEO assets.

The **Screening Volume** is the geometric volume placed around the asset during the conjunction screening process; any objects that violate this volume trigger data products to be generated and delivered. The screening volumes are sized by CARA using a 95% capture of the relative uncertainties in each orbital regime based two-year moving window historical conjunction data.

CARA Operations

- As CA data are received, the CARA system automatically processes those data, and generates & delivers
  - CARA Summary Reports to O/O
  - Worklist sent to CARA OSAs (ODs to examine)
- CARA Operations team performs routine risk analysis
  - Pc; Pc sensitivity
  - Conjunction Geometry
  - OD Evaluation / Solution Consistency
  - Space Weather Sensitivity
- Probability of Collision (Pc) for close approach events ranked by color:
  - Red Pc> 1×10^{-4}
  - Yellow 1×10^{-7}<Pc< 1×10^{-4}
  - Green Pc<1×10^{-7}
- For high-risk conjunctions, CARA produces/ delivers High Interest Event (HIE) briefing
  - Details, analysis results, recommendations
- If appropriate, CARA provides mitigation maneuver analysis and planning aids



$$P_c = P_0 + \int_{t_0}^{t_0+T} \left(\frac{dP_c}{dt}\right) dt$$ 1D time integral

$$\frac{dP_c}{dt} = \oint_{4\pi} I(\hat{\mathbf{r}},t)\, d^2\hat{\mathbf{r}}$$ 2D unit - sphere integral

The **Probability of Collision (Pc)** is the probability that, given the uncertainty in the two objects' positions as described by their covariance matrix, that the actual miss distance is less than the hard-body region