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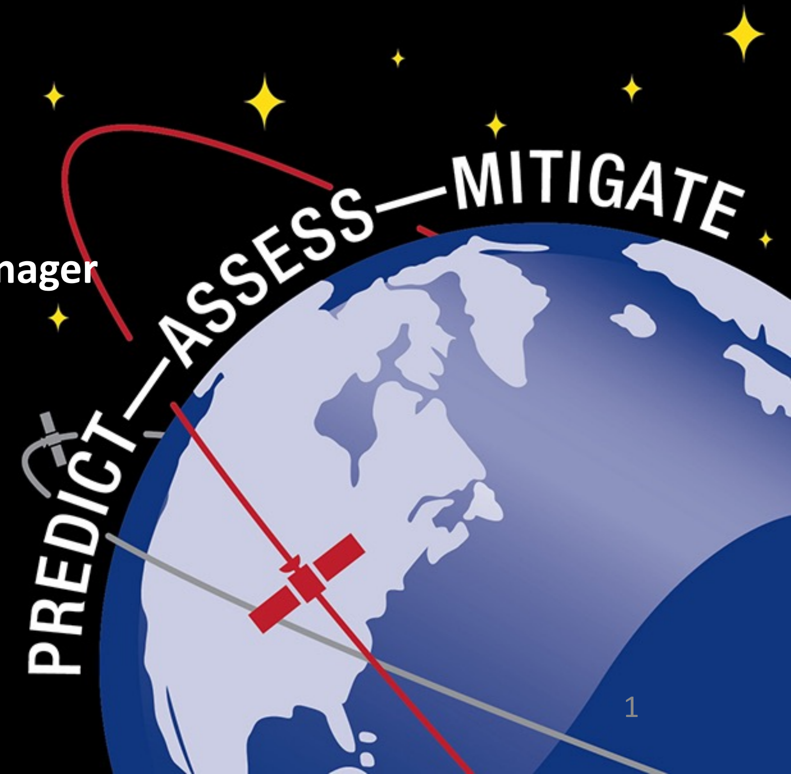
Conjunction Assessment: NASA Best Practices and Lessons Learned

Lauri K. Newman
NASA Conjunction Assessment Program Officer

Alinda K. Mashiku
Conjunction Assessment Risk Analysis (CARA) Program Manager

September 30, 2022



NASA Conjunction Assessment Risk Analysis

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Agenda

- Introduction to Conjunction Assessment at NASA
- NASA Best Practices Motivation
- Key Best Practices
- Challenges and Future Work

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Introduction to Conjunction Assessment at NASA

PREDICT—ASSESS—MITIGATE

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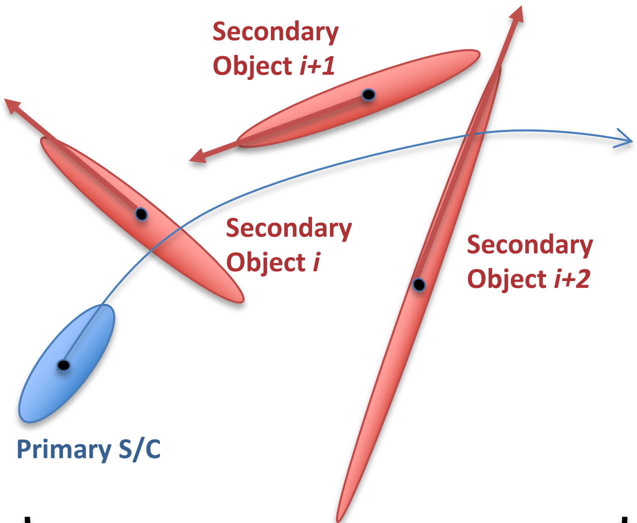
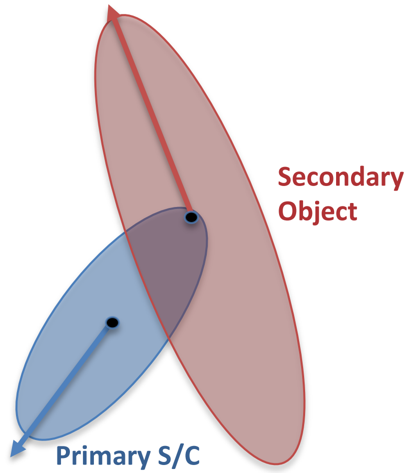
CA Operations: 3-Step Process



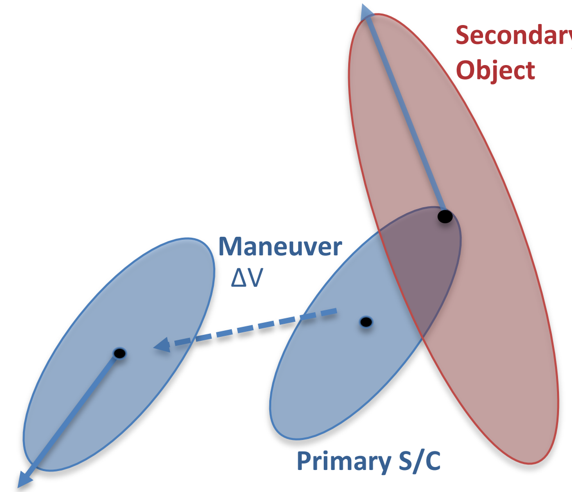
Conjunction Assessment (CA) is the process of identifying close approaches between two orbiting objects; sometimes called conjunction "screening".

The **18th Space Defense Squadron (18 SDS)** at Vandenberg SFB maintains the high accuracy catalog of space objects. Orbital Safety Analysts (OSAs) at VSFB screen protected assets against the catalog, perform tasking requests, and generate close approach data.



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

The NASA **CARA** program performs risk assessment for all NASA operational non-human space flight (HSF) satellites, and some partner missions. JSC performs risk assessment for all NASA HSF program assets and also performs maneuver decisions and execution.



Collision Avoidance 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 – is responsible for making maneuver decisions and executing the maneuvers.

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NASA CA Best Practices Handbook

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NASA Best Practices Motivation

- **Debris-producing space events have potential to make LEO unusable**
- **Experienced Conjunction Assessment (CA) practitioners have established approaches to minimize this risk**
- **Many space actors do not use these established approaches**
  - **No one international standard set of CA guidelines / best practices**
  - **Many Owner/Operators (O/O's) unaware of best practices**
  - **Some O/Os presume CA will be burdensome**
- **NASA collected its CA best practices and published them to assist other operators in maturing their practices and keeping space safe and accessible**

NASA Best Practices Handbook

- **NASA Spacecraft Conjunction Assessment and Collision Avoidance Best Practices Handbook** **https://nodis3.gsfc.nasa.gov/OCE_docs/OCE_51.pdf**
- **Helps space system operators understand existing capabilities and processes**
  - **Includes related US Space Command (USSPACECOM) and the US Space Force 18th Space Defense Squadron (SDS) best practices**
- **Provides technical background on NASA CA processes, including why requirements were levied and how to implement them**
- **Offers best practices for use by any spacecraft Owner/Operator to help protect the space environment**
- **Companion software repository contains many of the tools used by NASA:** ***https://github.com/nasa/CARA_Analysis_Tools***

Key Best Practices

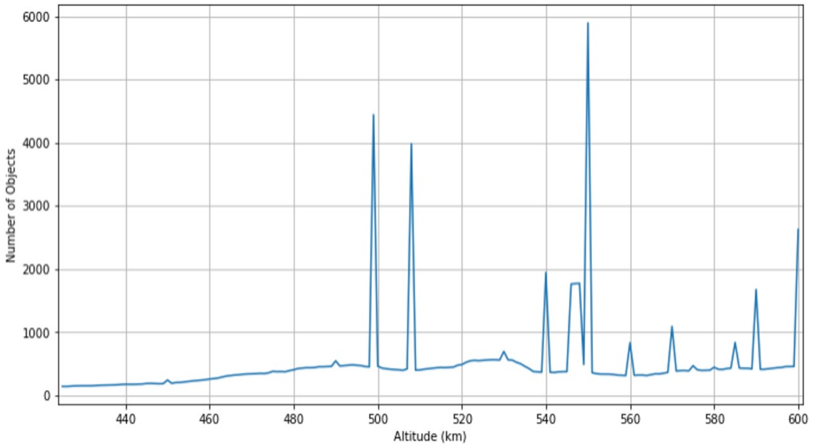
NASA **Conjunction Assessment Risk Analysis**

Spacecraft Design Considerations

- It is important (and efficient) to make plans for conjunction assessment during spacecraft planning and design
  - CA process needs can be accommodated more easily prior to spacecraft fabrication
  - Develop and validate all processes and tools well in advance of launch
- Key items to consider during design:
  - Orbit selection
  - Trackability
  - Deployment plan
  - Ephemeris generation process and tools
- Lesson learned example:
  - A NASA spacecraft assumed that two-line elements (TLEs) would be available for use in providing acquisition data to tracking radars.
  - After launch, it was discovered that the orbit was too low an inclination for DOD CA sensors to reliably track and maintain it, so TLEs were not available.
  - This situation could have been prevented through pre-launch analysis

Orbit Selection

- **Orbit Altitude Affects Event Rate:**
  - **Small changes in orbit altitude may make large differences in the number of close approaches**



*NASA CARA Program. (2019) Unpublished internal data.

- **Co-Location:**
  - **Determining in advance that there are other neighbors in the intended location of the spacecraft allows planning of communication and space sharing operations concepts.**

- **Transiting to final orbital position can create CA complexities**
  - **Transiting spacecraft should yield way to on-station spacecraft**
  - **Frequent, sometimes constant, maneuvering must be modeled in ephemerides provided to 18 SDS to communicate position to neighboring spacecraft**
  - **Transiting through constellations or large groups of active payloads requires frequent contact with other O/Os to adjudicate close approaches**

Trackability [1 of 2]

- Technology advances make possible spacecraft that are too small to be tracked by the Space Surveillance Network (SSN)
  - SSN is the DOD USSF resource assigned to track all on-orbit objects
  - Objects must be >10 cm to be tracked reliably in LEO
  - Objects must be >50 cm to be tracked reliably in GEO
  - Passive tracking not currently available beyond GEO (e.g., cis-lunar)
  - CA can be performed only against well tracked objects in the catalog

- Un-trackable objects on orbit pose a threat to flight safety
  - Objects in low inclination orbits (fewer SSN sensors with geometric visibility)
  - Objects in eccentric orbits (perigee can be away from radars and satellite can be too dim at apogee for optical sensors)

Trackability [2 of 2]

- **Potential workarounds include:**
  - Provide O/O ephemerides (does not work after end of operations)
  - On-board tracking radio beacon to provide position and ID
  - Corner cubes and an arrangement with a laser tracking facility to track and identify the payload
  - Coded light signals from a light source on the exterior of the spacecraft
  - Radio frequency interrogation of an exterior Van Atta array
  - Passive increase of albedo

- **Best Practice:**
  - Ensure objects are large enough to be tracked passively on-orbit. This enables tracking even after the spacecraft is no longer operational, until demise.
  - At injection, make sure object is placed far enough away from other deployed satellites and on-orbit objects to allow unique, unambiguous tracking

Deployment Plan

- Issue: complex deployments create cataloguing difficulties
  - Rapid child deployments proliferate deployed satellites, when parents may already be difficult to distinguish, track, and catalog depending on number of objects deployed
  - Tethered deployments follow non-Keplerian trajectories; difficult to maintain orbit in catalog
- Approach: attempt to simplify/prepare for situation
  - Delay child deployments until 18 SDS is able to catalogue parent
  - For tethered deployments, work out tracking/maintenance strategy with 18 SDS in advance of launch
- Rideshare missions must rely on launch provider to protect their spacecraft by using safe deployment practices

Ephemeris Generation Process and Tools: Producing a CA-Quality Ephemeris

- Since close approaches are computed using predictions of future spacecraft position, those predictions must be accurate enough to enable maneuver planning.
- If spacecraft is not passively trackable or if it is maneuverable, predicted trajectory information must be provided to 18 SDS to enable close approach computation.
  - At least once per day
  - Predicted at least 7 days into the future
  - Quality modelling, especially atmospheric drag, must be used to reduce errors
  - Include realistic covariances
- Two Line Elements (TLEs, e.g. obtained from SpaceTrack.org) are <u>NOT SUFFICIENT</u> FOR CA
  - 1-2 km theory error is too large for maneuver planning
  - No covariance available to compute probability of collision and make risk decision
- Maintain Space-Track.org information,
  - Contact information (24x7, since other O/Os may be in a different time zone)
  - Active and maneuverable status flags

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Challenges and Future Work

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Satellite Autonomous Maneuvering

- Becoming more common for satellites to employ autonomous maneuvering (especially large constellations)
  - Current example: SpaceX's Starlink, ~2000 active satellites operated this way
- Maneuvers automatically commanded/executed
  - Often ground systems do not even know of maneuvers until after execution
- CA can also be executed autonomously
  - Conjunction Data Messages (CDMs) for upcoming conjunctions uploaded to spacecraft
  - On-board CA software can determine risk based on spacecraft's latest position information, plan maneuvers to avoid close approaches, and execute them
  - If CDMs generated with sufficiently large screening volume, then autonomous CA likely to be effective against debris

Autonomous Flight Dynamics: Active-vs-Active CA Issue

- Autonomous systems program maneuvers and perform CA based on CDMs uploaded as frequently as contacts allow
- Co-located autonomously-controlled constellations need other solutions
  - Two satellites in conjunction from different constellations may be planning mitigation actions, but neither knows what the other is planning to do
  - Satellites could therefore maneuver into each other
- For autonomous CA with other active satellites, latencies in information exchange cause CA problems
  - Non-autonomous active satellites need to refrain from maneuvers 12-24 hours before close approaches with autonomous satellites
  - Allows sufficient time for submitted ephemeris that includes their maneuver to be screened for CA and these screening results uploaded to autonomous system

Active-vs-Active CA Issue: Current Resolution Efforts

- NASA is part of an industry consortium to develop a pathfinder solution
  - NASA experimental autonomous constellation (Starling) will be collocated with Starlink constellation, forcing the issue
  - Consortium among NASA Ames, NASA CARA, SpaceX, Emergent Technologies, and UT Austin to develop and demonstrate a prototype autonomous CA approach
  - "Mother May I" solution utilized
- Infrastructure being built out. Ground testing underway
- Department of Commerce (DOC) participates in observer status
  - Designated to assume space traffic management responsibility
  - Successful demonstration of approach expected to be embraced by DOC
- Day-long session on this issue and investigated approaches to be presented in a conference venue this coming winter

Cis-lunar CA

- Catalog of non-cooperatively/passively tracked objects used in CA only available near Earth
- Activity at Moon, Mars, and Libration points increasing risk of collision without screening
  - NASA MADCAP provides ephem-on-ephem screening for missions
  - Relies on sharing of data; open to non-NASA entities
- DOD developing cis-lunar catalog and screening capability
  - Requirements not yet defined
  - Implementation is still in the early stages of development
- NASA continues to work with DoD on beyond GEO SSA capabilities.

Summary

- Increasing congestion of space accentuates need to follow CA best practices
  - Particularly/especially in LEO
- Best Practices are incorporated most cheaply/efficiently when designed in from the beginning
- NASA CARA committed to develop/refine appropriate best practices
  - Integrate feedback from space operators
  - Expand coverage to address emerging areas of interest
  - Continue to focus on a safe space environment for all operators

NASA CA Handbook | CARA Tool Repository | NASA CA website

Questions?

Active-vs-Active CA Issue Potential Solution: "Mother May I" Approach

- Ground hub established to receive ephemerides from autonomously-controlled constellations
- If a satellite wishes to maneuver, assembles proposed maneuver ephemeris and submits to ground node
- If ephemeris does not produce any CA issues, ephemeris is "cleared" for use, and message sent to constellation indicating this
  - Submitting satellite now has a "right" to this ephemeris, and other satellites prevented from (voluntarily) impinging on it
  - Submitting satellite also has an obligation to follow this ephemeris unless they subsequently submit an alternative, which is itself cleared
- System can also allow the submission of multiple, ranked maneuver ephemerides at the same time
  - Highest-ranked ephemeris that does not produce CA issues "cleared" for use
- Approach requires contact times frequent enough to enable communication of plan between spacecraft and ground at appropriate times

Active-vs-Active CA Issue Potential Solution: Rule-Based Approach

- Set of rules could be developed that would make clear, in every conjunction, which satellite should perform which actions
  - Iridium proposed a set of such rules in a recent paper
- If this approach is possible, could eliminate need for "mother may I" communication approach described previously
- However, some scenarios may not be sufficiently addressed:
  - Example: Suppose two autonomous spacecraft each need to perform a maneuver
  - Each schedules one, unaware the other has done so, creating a conjunction
  - Unless the maneuvers are planned well in advance (more than 24 hours, to allow the present system to screen submitted ephemerides and send back CA results), no way for both satellites to know they are creating a risky conjunction
  - No easy way to resolve who is permitted to maneuver