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SAFE SPACE CONDUCT: NASA BEST PRACTICES FOR SMALLSATS

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NASA **Conjunction Assessment Risk Analysis**

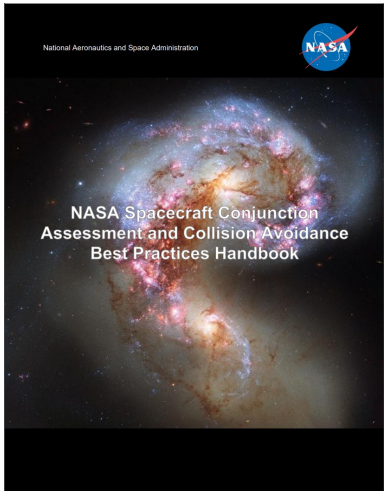
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Agenda

- Background
- Ephemeris Generation
- Trackability
- Autonomous Satellite Maneuvering

Background

- 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, or presume CA will be burdensome, when it really isn't
  - Implementation of best practices is easier during spacecraft design
- NASA collected its CA best practices and published them to assist other operators in maturing their practices and keeping space safe and accessible
  - "NASA Spacecraft Conjunction Assessment and Collision Avoidance Best Practices Handbook"
  - Available at https://nodis3.gsfc.nasa.gov/OCE_docs/OCE_51.pdf



NASA Best Practices Document: Genesis and Structure

- **Product of interagency working group**
  - **NASA's Conjunction Assessment Risk Analysis (CARA) program, NASA Human Spaceflight (HSF) CA team, and Department of Defense (DoD) (US Space Force/Delta 2, US Space Command)**
  - **Reviewed by Department of Commerce and certain industrial actors**
- **Five major divisions, corresponding to spacecraft phases of life**
  - **Design phase, pre-launch, launch and early-orbit, on-orbit, and deorbit/disposal**
  - **Each division has multiple subdivisions, and each subdivision includes multiple best practices, with justification and commentary**
- **Sixteen technical appendices**
- **Purpose of today's presentation not to summarize entire document but to discuss in some detail three areas of relevance to small satellites**
  - **Ephemeris generation**
  - **Object trackability**
  - **Autonomous satellite maneuvering for flight control and CA**

Motivation: Why is CA important for Smallsats?

- **Conjunction risk, and therefore needed mitigation actions, computed using position predictions (and their associated uncertainties) for the two objects**
  - **For large active satellites conjuncting with smaller debris objects, position prediction for debris object usually dominates calculation (much higher uncertainty)**
  - **For small satellites against larger, inactive secondary objects (e.g., rocket bodies), situation is reversed: position of smaller satellite likely to be dominant factor**
    - **Collisions with large objects produce large amount of debris**
- **Important, therefore, to have good predicted future positions for smallsats**
- **DoD orbit predictions for smallsats often not sufficient to meet CA need**
  - **If satellite can change trajectory (impulsive maneuver, low-thrust maneuver, differential drag), DoD solution cannot account for such changes**
  - **Smaller satellites tracked less frequently by DoD (fewer sensors that can track small objects), producing less accurate updates and predictions**
- **During spacecraft design phase, need plan to produce and share CA quality ephemeris**
  - **Determine that DoD solution is adequate or plan for O/O to produce/share ephemerides**

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Ephemeris Generation



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Ephemeris Generation and Sharing: Producing a CA-Quality Ephemeris

- Quality on-board GPS receiver (now quite affordable) or other tracking data (next topic)
- Quality orbit determination software
  - NASA software (e.g., GMAT, MONTE) and commercial products (e.g., ODTK, FreeFlyer) are readily available
- Precision propagation with numerical integration and proper perturbation modeling
  - Geopotential modeling: at least 36 x 36 for LEO
  - Third-body effects (solar/lunar perturbations)
  - Atmospheric drag—usually the most problematic perturbation (orbits < ~1000 km)
    - Modern drag models (JB08, MSIS, DTM)
  - Solar radiation pressure (orbits > ~500 km)
- Two Line Elements (TLEs, e.g. obtained from SpaceTrack.org) NOT SUFFICIENT FOR CA
  - 1-2 km theory error too large for maneuver planning
  - no covariance available to compute probability of collision and make risk decision

Ephemeris Generation and Sharing: Predicted Ephemeris Characteristics

- CA always performed in prediction
  - Prediction error mechanisms are typically more important than epoch error
- Greatest source of "prediction error": planned maneuvers
  - Principal advantage of O/O ephemerides—to include planned maneuvers in ephemerides so that CA screenings will reflect expected future satellite position
  - Especially important for low-thrust / differential drag missions, in which maneuver detection will be especially difficult
- Predicted atmospheric density greatest predictive astrodynamics problem
  - Debiasing techniques, such as HASDM, are helpful for reducing global density model error in immediate future
  - Need to carefully set process noise or consider parameters in order to ensure covariances in ephemeris are properly sized to encompass density forecast errors
  - Approaching solar maximum will cause increased uncertainty in the atmospheric density prediction, complicating CA

Ephemeris Generation and Sharing: Ephemeris Frequency and Fidelity

- **Generate/submit to DoD 18th Space Defense Squadron (18 SDS) or other provider at least one predicted ephemeris per day**
  - **3 times/day preferable for orbits < 500 km**
  - **Resubmit after major state updates (e.g., maneuvers)**
- **Produce predicted ephemerides several days into the future**
  - **Current standard is 7-day ephemerides for LEO; 10-day ephemerides for HEO/GEO**
- **Provide ephemeris point spacing of ~1/100th of an orbit**
  - **Typically met by 1-minute spacing for LEO and 10-minute spacing for GEO**
  - **For HEO, can regularize by even spacing in true anomaly**
- **Ensure covariances in ephemeris be realistic**
  - **Itself a discipline; NASA CARA website has documentation and assessment tools**
  - **Link: https://www.nasa.gov/conjunction-assessment**

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Satellite Trackability



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SmallSat Trackability/Maintainability

- **Important for CA that the position of SmallSats be determinable to a level of accuracy/precision that will enable an accurate ephemeris**
  - **"Trackability" is term that has traditionally, but perhaps not entirely appropriately, been used to describe this**
    - **Some objects can be tracked occasionally but not sufficiently frequently, or with enough distribution of tracking about the orbit, to be modeled well**
    - **Perhaps "adequate orbit maintenance" a better locution**
  - **Many O/O's assume that DOD tracking is always available, but this may not be true using CA sensors given the orbit and size of the object**
- **During operations, adequate predicted position can be accomplished via sharing ephemeris; but what about mission anomalies or after passivation?**
  - **Self-powered beacon to transmit position (even in cases of satellite failure/passivation)**
  - **Satellite passively trackable by a SSA provider**
- **Adequate orbit knowledge of smallsats becoming critical as space becomes more congested**

Trackability/Maintainability Rules of Thumb

- **Object trackability is a function of multiple factors**
  - **Geometric visibility of orbit to sensors, distance from sensor to satellite, and satellite's propensity to sensor detection (size and material composition)**
- **Rules of thumb for SSN tracking**
  - **Objects larger than 10 cm and in "regular" LEO orbits (400-700km circular and not at low inclination) can be reasonably presumed to be trackable**
  - **Objects larger than 1 m at GEO must be larger to be passively tracked by SSN CA sensors**
  - **Non-cooperative tracking not currently available beyond GEO (e.g., cis-lunar)**
- **Problematic for tracking:**
  - **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)**
- **Rules of thumb for adequate maintenance**
  - **> 1 track per day, in stable orbits, generally produces CA-enabling maintenance**
  - **More heavily perturbed orbits or eccentric orbits will require more tracking**
    - **In such cases, need tracking around the orbit in order to ensure adequate modeling**

Trackability/Maintainability Determination

- 18 SDS can be asked to perform maintainability analysis
  - Due to volume of such requests, may not be able to respond
- Other commercial providers can be retained
  - E.g., LeoLabs for LEO, ExoAnalytics or Numerica for HEO/GEO
  - Would be able to perform their own assessments
- Trackability can be improved via:
  - 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
- NASA CARA working to make more trackability/maintainability information available in Best Practices forthcoming update
  - More information on orbit quality necessary for robust CA
  - Better-defined ruleset for anticipated tracking receipt

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Autonomously-Controlled Satellites



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Satellite Autonomous Maneuvering

- Becoming more common for satellites to employ autonomous maneuvering (especially large constellations)
  - SpaceX's Starlink current example: ~2000 active satellites operated this way
  - Other, smallsat autonomous constellations planned
- Autonomous flight dynamics has some common features:
  - After injection, autonomously follow master trajectory to reach on-station position
  - Once on-station, orbital elements kept within certain boundaries
  - In both cases above, maneuvers automatically commanded/executed
    - Often ground systems do not even know of maneuvers until after execution
- CA can also be executed autonomously
  - 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 static captures of their CA situation, uploaded as frequently as contacts allow**
  - **Mechanism for informing satellites of upcoming conjunctions with debris**
- **For 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**
  - **Co-located autonomously-controlled constellations produce irresolvable situation**
    - **Two satellites in conjunction from 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**
    - **Not merely a fanciful situation: in famous Iridium-COSMOS collision, Iridium has stated that their satellite maneuvered into the COSMOS trajectory due to lack of available CA data**
      - **This situation led the advancement of the CA process to what we know and use today**

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
  - But 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

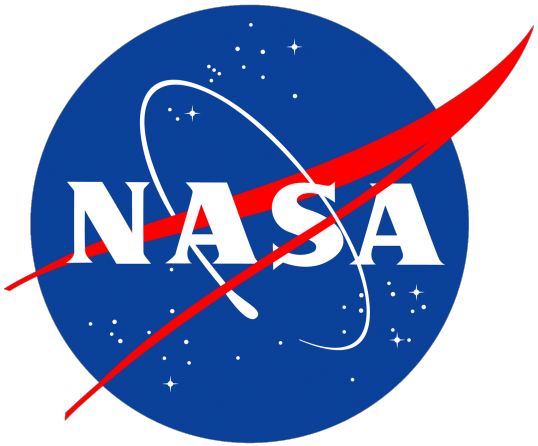
- Set of rules could be developed that would make clear, in every conjunction, which satellite should perform which actions
  - Iridium proposed set of such rules in a recent paper
- If approach possible, could eliminate need for communication approach and system described previously
- However, some 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 ephems 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

Active-vs-Active CA Issue: Current Resolution Efforts

- NASA is part of an industry consortium to develop 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 is favored approach at present
- 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 lead to embrace by DOC
- Day-long session on this issue and investigated approaches to be presented in a conference venue this coming winter

Summary

- **Increasing congestion of space accentuates need to follow CA best practices**
  - **Particularly/especially in LEO**
- **Three areas of particular relevance to smallsats:**
  - **Ephemeris generation and sharing**
  - **Trackability**
  - **Autonomous maneuvering without sharing plan**
- **Best Practices are incorporated most cheaply/efficiently when designed in from the beginning**
- **NASA CARA committed to develop/refine appropriate best practices**
  - **Balance maintaining flight safety against minimizing burden on smallsat missions**
  - **NASA CA website has other helpful CA education information:** https://www.nasa.gov/conjunction-risk-analysis-and-mitigation


NASA

Acronyms

18 SDS	18th Space Defense Squadron
CA	Conjunction Assessment
CARA	Conjunction Assessment Risk Analysis
O/O	Owner/Operator
TLE	Two-Line Element
CDM	Conjunction Data Messages
SSN	Space Surveillance Network
GEO	Geostationary/Geosynchronous Orbits
LEO	Low Earth Orbits
HEO	Highly Elliptical Orbits
HASDM	High Accuracy Satellite Drag Model

References/Useful Links

Handbook of Best Practices:
https://nodis3.gsfc.nasa.gov/OCE_docs/OCE_51.pdf

CARA software repository: https://www.nasa.gov/conjunction-assessment

NASA CA Website: https://www.nasa.gov/conjunction-risk-analysis-and-mitigation

Iridium paper on rules of the road: *Shepperd, Ryan W. and Kristina C. DiOrio, "The Time for a Set of Traffic Rules has Arrived," AAS 20-639.*

Iridium paper on collision: Proceedings from Kinetic LEO Space Safety Workshop, May 2022, https://kineticspacesafety.com/