Conjunction Assessment: NASA Best Practices and Lessons Learned

Lauri K. Newman
NASA Headquarters

Alinda K. Mashiku
NASA Goddard Space Flight Center

Abstract

In December 2020 the National Aeronautics and Space Administration (NASA) published a Spacecraft Conjunction Assessment and Collision Avoidance Best Practices Handbook. This paper describes how Owners/Operators (O/Os) can use the NASA Handbook to assist in developing a robust conjunction assessment operations process, as well as presenting examples of responsible practices for spacecraft O/Os to consider for lowering collision risks and operating safely in space (from Low Earth Orbit [LEO] and beyond) in a stable and sustainable manner. Consideration is given to important topics such as spacecraft and constellation design; spacecraft "trackability;" pre-launch preparation and early launch activities; on-orbit collision avoidance; and automated trajectory guidance and maneuvering. The paper also addresses parts of the Handbook that have proven to be problematic for O/Os and the studies and analyses NASA is pursuing to create workable alternatives.

Introduction

A significant increase in the volume and diversity of activity in space means that it is becoming increasingly congested. Emerging commercial ventures such as satellite servicing, in-space manufacturing, and tourism, as well as new technologies enabling small satellites and large constellations of satellites, present serious challenges for safely and responsibly using space in a stable, sustainable manner. To meet these challenges, the U.S. seeks to improve global awareness of activity in space by publicly sharing flight-safety-related information and by coordinating its own on-orbit activity in a safe, responsible manner. It seeks to bolster stability and reduce current and future operational on-orbit risks so that space is preserved for future generations.

To that end, in December 2020 the National Aeronautics and Space Administration (NASA) published the " NASA Spacecraft Conjunction Assessment and Collision Avoidance Best Practices Handbook[*] " (referred to hereafter as the CA^2 Handbook) that reflects how NASA currently operates. Owners/Operators (O/Os) can use the guidance and technical appendices in the NASA Handbook to assist in developing a robust conjunction assessment operations process that enables lowering collision risks and operating safely in space (from Low Earth Orbit [LEO] and beyond) in a stable and sustainable manner.

Because conjunction assessment is a relatively new field, it has not seeped into the mission design and development process; and many spacecraft O/Os have addressed it only just prior to or after launch. However, at that point, changes to software are difficult and changes to hardware are nearly impossible. Yet small changes made during spacecraft design can have a great effect on the ability of a spacecraft to avoid or mitigate close approaches with other spacecraft. In this paper, the authors focus on several important topics from the CA^2 Handbook that are best addressed during spacecraft formulation and design. The covered topics directly affect the ability to perform robust conjunction assessment, but they are often overlooked because they are not part of the on-orbit screening or risk assessment activities usually associated with CA. These topics include orbit selection, spacecraft trackability, production of ephemerides with covariance, deployment strategy, interface establishment to facilitate data exchange with other O/Os and stakeholders, autonomous control, and non-Earth centered CA.

<u>Choosing a Mission Orbit</u>

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[*]NASA Spacecraft Conjunction Assessment and Collision Avoidance Best Practices Handbook, NASA/SP-20205011276, December 2020, ***https://nodis3.gsfc.nasa.gov/OCE_docs/OCE_51.pdf*.**

An orbit that results in a high number of close approaches with other satellites can lead to the need to perform many conjunction risk mitigation maneuvers, each of which may not fully mitigate the risk of collision. Spacecraft that cannot maneuver have no way to mitigate collision risk and thus will operate at higher risk of collision, effectively presenting additional risk to other spacecraft.

Orbit selection should be informed by a study to determine expected conjunction rates. That is, the expected number of lifetime conjunction risk mitigation maneuvers and the amount of satellite fuel needed to allow safe operation for the desired number of years on orbit. For instance, if a spacecraft is being designed to fly “near” 500 km, a plot of orbit density (see Figure 1 below) shows that small changes in mission altitude to target 480 km or 520 km instead would drastically reduce the number of close approaches that would require, at a minimum, specialized analysis and, with some frequency, mitigation actions. Performing this trade during satellite design allows maximum flexibility in mission planning to reduce the effect of conjunction assessment processing during operations. This is one of the first trades that should be performed, since the choice of orbit affects many other aspects of the spacecraft design.

Unfortunately, performing the analysis is not always as straightforward as obtaining Two-Line Elements (TLEs) from Space-Track.org, the United States Space Command (USSPACECOM) website, and performing an object count. That is certainly the correct initial step, but mission designers also need an understanding of future missions planned for the chosen altitude, since it could be years before flight of the spacecraft being designed, and the orbit environment could change significantly during that time. However, it is difficult to obtain accurate predicted future orbit population information. There are many available sources, and all offer speculative but not definitive information. For instance, one source of predicted future orbit population is publicly-available launch license applications from the Federal Communications Commission (FCC) or the Federal Aviation Administration (FAA). Launch and payload license applications show only what MAY happen, not what will happen; but it is important to maintain at least some awareness of expected trends and developments by altitude.

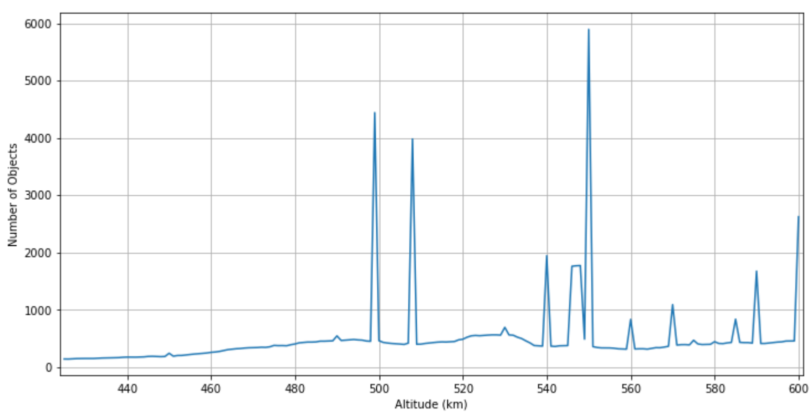

Figure 1: Example Plot Showing Number of Objects by Altitude [from NASA Conjunction Assessment Risk Analysis (CARA) Study]

<u>Trackability/Catalog Maintenance</u>

Predicting close approaches requires an accurate orbital state for both objects. The USSPACECOM space object catalog maintained at Vandenberg Space Force Base uses the data collected by the Space Surveillance Network (SSN) to compute and maintain states for all on-orbit objects. Because the data are not supplied by the O/O, it is referred to as non-cooperative tracking data. Since active spacecraft become debris after their end-of-life, any ephemeris data available while the object is in use by the O/O, deriving from on-board Global Positioning System (GPS) receivers or other active tracking mechanisms, would not be available once the spacecraft is no longer in use; non-cooperative tracking will therefore be important to obtain an orbit solution once the mission is passivated. All launched satellites should thus be acquirable and trackable by the SSN, or another non-cooperative tracking provider that is expected to be operating over the entire lifetime of the satellite, so that the satellites can be cataloged and maintained using non-cooperative tracking capabilities alone to enable other O/Os to know where the spacecraft is for close approach prediction. Launching a spacecraft that is not trackable by a non-cooperative provider increases risk to all O/Os for the entire period that the passivated (or failed) mission remains on orbit.

Objects are “trackable” if they have a large enough radar or optical cross section to be tracked by at least two sensor assets. Analytical evaluations of trackability consider object size, material properties, and orbit; so there is no absolute size threshold that is determinative. As a rule of thumb, satellites need to have characteristic measurements of 10 cm in each major dimension for spacecraft with perigee less than 2000 km and greater than 50 cm in each major dimension for spacecraft with perigee greater than 2000 km.

As an example, there was a NASA mission that chose to fly in a low inclination LEO orbit. The O/O assumed TLEs would be available for their use as acquisition data; and since precision position data were not needed for this particular mission, no precision navigation option was implemented. After launch, the O/O noticed that TLEs for their object were not regularly updated on Space-Track.org, with gaps as long as 10 days at a time. Position data that old were not sufficiently accurate to enable satellite acquisition, and mission success was thus threatened. Investigation by the NASA Conjunction Assessment Risk Analysis (CARA) team showed that the spacecraft was frequently not visible to the SSN sensors used for CA due to the satellite’s low inclination. The spacecraft O/O was, after the mission was already launched, forced to look for other options, such as updating the on-board GPS (that was configured only for science) to be used for navigation, or to buy commercial tracking data. These solutions were viable but not within the allocated budget, and it would take time to write the necessary software or set up the necessary contracts. This situation could have been avoided by a small trackability study performed during the design phase. NASA now requires all of its spacecraft to perform such an analysis as part of mission design.

Ephemeris Production

For missions that make changes to their orbit via non-Keplerian means (propulsive maneuvers, differential drag, etc.), non-cooperative tracking data does not enable sufficiently accurate predicted orbit solutions for Conjunction Assessment purposes. The O/O must produce and share with USSAPCECOM and other O/Os ephemerides that include planned trajectory changes so that resulting close approaches can be accurately predicted and mitigated.

To enable CA screening, predicted ephemerides must be furnished routinely, typically at least daily for LEO spacecraft, and also immediately following any planned or executed trajectory change. Ephemerides must span an appropriate period of predictive time for the screening being performed. A typical duration is seven days for LEO spacecraft. The ephemeris point-spacing must be sufficiently close to enable interpolation; usually one-minute spacings in LEO and ten-minute spacings in higher circular orbits are adequate, but a Highly Eccentric Orbit (HEO) often will require regularized spacing in true anomaly. A full state (position and velocity) and a realistic 6 x 6 (or larger) covariance matrix (with both variance and covariance terms) should be included for each ephemeris point (see the CA^2 Handbook for more details about covariance realism characterization and evaluation). The software and process components of the CA risk assessment and mitigation capabilities drive design of elements of both the flight hardware and the ground system, and both should be fully developed and tested before launch.

Some O/Os are reluctant to share their predicted ephemerides because they view this information as proprietary. Experienced commercial O/Os and NASA agree that any concerns about predicted position and associated covariance data being proprietary are not well founded, as publicly-available trajectory data such as TLEs are generally close enough to the maneuver trajectory to reveal quite a bit about the satellite’s trajectory, regardless of availability of the maneuver ephemerides. However, the predicted maneuver data IS needed for accurate close approach computation, so any residual proprietary concern is outweighed by the safety benefit of exchanging such information.

The importance of generating quality ephemerides with covariance was illustrated recently by a NASA mission that was not able to generate quality predictions or a realistic covariance, so the O/O data used in their CA calculations was not representative of their actual trajectory. Calculations based on the mission-provided ephemeris diverged regularly from the 18 Space Defense Squadron (18 SDS) calculations and identified many more serious conjunctions than did the 18^{th}-based calculations; and all of these elevated alerts turned out to be spurious. Nonetheless, each one had to be investigated by CARA and the mission to determine that the event was in fact not legitimate, wasting a large amount of both groups’ engineering time and effort. It then required a significant amount of analysis investment for the mission to improve their ephemeris and covariance generation capability because their ground system was not configured to allow easy tuning and modification of the relevant orbit determination (OD) parameters. If ephemeris production functionality had been developed during the mission design phase, this operational issue may have been greatly reduced or avoided entirely.

Deployment Strategy

One factor that is determined well before launch but can have critical consequences post-launch is the selection of a satellite deployment strategy. Often spacecraft O/Os have only limited influence over this, as the deployment methodology is established by the launch vehicle. However, some spacecraft then subsequently deploy child spacecraft, in which case they fully control the child spacecraft deployment. Factors in deployment methodology that affect the ability of non-cooperative tracking entities to catalog newly-deployed satellites and thus get them into the CA process as quickly as possible include managing the number of objects deployed, throttling the timing between multiple deployments, and waiting to execute child deployments until the mother spacecraft has itself been catalogued and entered into the CA process. Examples of unusual deployment features that might create cataloging issues include high-velocity deployments and tethered satellites. Additionally, multiple, nearly-simultaneous deployments are a challenge for tracking and will delay cataloging, which in turn poses a safety-of-flight risk. Deployments should be spaced to allow acquisition of each object. For multiple nearly-simultaneous deployments, the expected range of deployment speeds and directions should be provided to USSPACECOM for aid in cataloging the deployed objects. Additionally, O/O ephemerides generated once contact is made with each deployed vehicle can both assist the cataloguing process and be used as an input to CA activities, even in advance of formal cataloguing. Finally, to aid in satellite tracking and identification, injection vector(s) should be provided to USSPACECOM as soon as they are available.

A regularly-encountered problem with spacecraft deployment timing are the launches by a US commercial O/O who deploys 50 spacecraft simultaneously. It takes two full-time operators over a week to establish spacecraft identity and add these spacecraft fully to the catalog, meaning that orbital safety activities during that period must resort to non-standard processes that are not fully sufficient for CA. In this case, it is likely that modifications both on the deployment side and at the cataloging side are necessary to resolve the problem; having time to address this issue during the spacecraft design phase would have been helpful to establish the parameters of a solution before encountering it operationally.

Establishing Interfaces

Prior to launch, the interfaces for exchanging CA data should be established and tested. One important interface is USSPACECOM (e.g. 18 SDS). USSSPACECOM distributes Conjunction Data Messages (CDMs) through Space-Track.org. So O/Os should register on Space-Track.org and provide contact information to USSPACECOM to receive CDMs and to ensure that other O/Os can contact the right person in the event of a close approach. Space-Track.org also offers a set of flags that O/Os should set to let others know the status of their spacecraft (maneuverability, whether the spacecraft has experienced an anomaly, etc). Providing this information to Space-Track.org is important: it tells other O/Os if your satellite is maneuverable and therefore whether active coordination with you is necessary to mitigate a serious conjunction. If desired, a test instantiation of Space-Track.org is available to allow O/Os to practice generating, receiving, and processing CA data products.

Many commercial companies are now offering data and services for CA. Even if a spacecraft O/O chooses to use a commercial CA data provider, they are encouraged also to send ephemerides to 18 SDS, since other O/Os rely on data provided to 18 SDS for screenings. The 18 SDS service is free and may identify different conjuncting objects in the catalog than those found by the commercial provider. So, using 18 SDS data only improves CA.

Interfaces to the CA risk assessment provider should also be established and tested. 18 SDS provides only CA screening (identification of close approaches); the necessary subsequent effort to analyze those close approaches to determine which constitute high-risk events must be performed by the O/O or a service entity. Some O/Os choose to use TLEs as their data source for CA computation. However, TLEs do not contain covariance and therefore cannot be used to compute a probability of collision, which is the industry standard metric for CA risk assessment; and TLEs possess an inherent theory error of 1-2 km, so they will never model miss distance accurately enough to permit accurate mitigation maneuver planning. Space-Track.org states, and a consensus of CA risk assessment O/Os recognize, that TLEs should not be used for CA calculations.

Consideration should be given to whether an interface to the International Space Station office at NASA Johnson Space Center is desirable to coordinate passing of a spacecraft through the ISS regime. ISS offers ephemeris exchange to ensure safe passage to protect the astronauts. When deorbiting, care should be taken not to pass through the human spaceflight regime more than necessary and to keep all spacecraft operable until they pass below the ISS altitude.

Autonomous Control Considerations

The use of autonomous satellite flight dynamics, including autonomous orbit maintenance maneuvers and conjunction mitigation, has increased recently. A significant factor in this increase is the growing number of large constellation O/Os who need autonomy to handle the scaling of their system. Autonomous control becomes even more complicated when both spacecraft involved in a close approach are operating autonomously. Both could be planning maneuvers that lead to a collision if the O/Os do not share their maneuver plans with each other.

If a spacecraft is being designed to perform autonomous maneuvers, care should be taken to ensure that the predicted trajectory is shared with USSPACECOM (18 SDS) and that resulting CDMs are received onboard for analysis and mitigation action, with a sufficiently large screening volume used to give the autonomously-controlled spacecraft a "snapshot" of the space catalog in its vicinity. This additional information will allow the spacecraft to determine whether any contemplated maneuvers will create problematic conjunctions with other spacecraft. For this paradigm to be workable, however, all other maneuverable spacecraft in the vicinity of the autonomously-controlled spacecraft must ensure that their predicted ephemerides fully reflect intentions and that they not change their intentions without sufficient advance notice. Advance notice would need to be early enough to allow their intended trajectory, via an ephemeris, to be forwarded to 18 SDS and the resulting CDMs to be uploaded to the autonomous spacecraft. Because of the extra burden that autonomous control involves, a different method for adjudicating these problems is desired.

Recently, NASA developed Starling, an experimental constellation built to test autonomous flight dynamics/control and constellation reconfiguration. Due to Starling's planned ride-share, it will be essentially collocated with the Starlink constellation fielded by SpaceX, which also uses autonomous control. Thus, there is now a specific identified need to develop a safety solution that can be applied to this situation. A consortium was formed among NASA CARA (the group that performs CA for NASA uncrewed spacecraft), NASA Ames (the NASA center developing the Starling mission), Emergent Space Technologies (the contractor developing the autonomous control software for the Starling mission), University of Texas at Austin (the entity providing astrodynamics consulting and services to the Starling mission), and SpaceX (the operator of the Starlink constellation) to develop an appropriate solution, build out the needed software and ground node, and test the paradigm during the planned extended mission portion of the Starling mission. A public forum is planned for fall/winter 2022-23 to present the proposed solution and solicit feedback from the broader community.

Cis-lunar and Non-Earth Centered CA

The standard CA process is applicable only for spacecraft orbiting the Earth within the geosynchronous altitude, as that is the area of space for which there is a non-cooperatively-tracked catalog of space objects. Tracking of objects further away requires different hardware and techniques, and a consolidated plan to create a catalog of such objects for CA screening is not yet readily available despite the growing interest in cis-lunar space activities. The U.S. Department of Defense (DOD) is working on developing a cis-lunar catalog and screening capability similar to the current 18 SDS Earth-based process, but the cis-lunar capability is still in the beginning stages. In the interim, NASA has created a screening service using O/O-provided ephemerides for the moon, Mars, and several of the libration points. All NASA spacecraft are required to participate in this Multi-mission Automated Deep space Conjunction Assessment Process (MADCAP) process; non-NASA entities are encouraged to share ephemerides and participate in the screening service.

Summary

NASA plans to continue to update the CA^2 Handbook as the state of the art continues to change and updates are warranted. For example, once a durable proposal for the interaction of autonomously-controlled constellations is reached, the Handbook will be updated to reflect this development and provide an extended explanation and technical treatment.

For more information on topics mentioned in this paper and other related items, visit the NASA CA website at https://www.nasa.gov/conjunction-risk-analysis-and-mitigation.

ACKNOWLEDGEMENT:

The authors would like to thank Dr. Matthew Hejduk for his contributions to the NASA CA^2 Handbook and thus also to this paper.