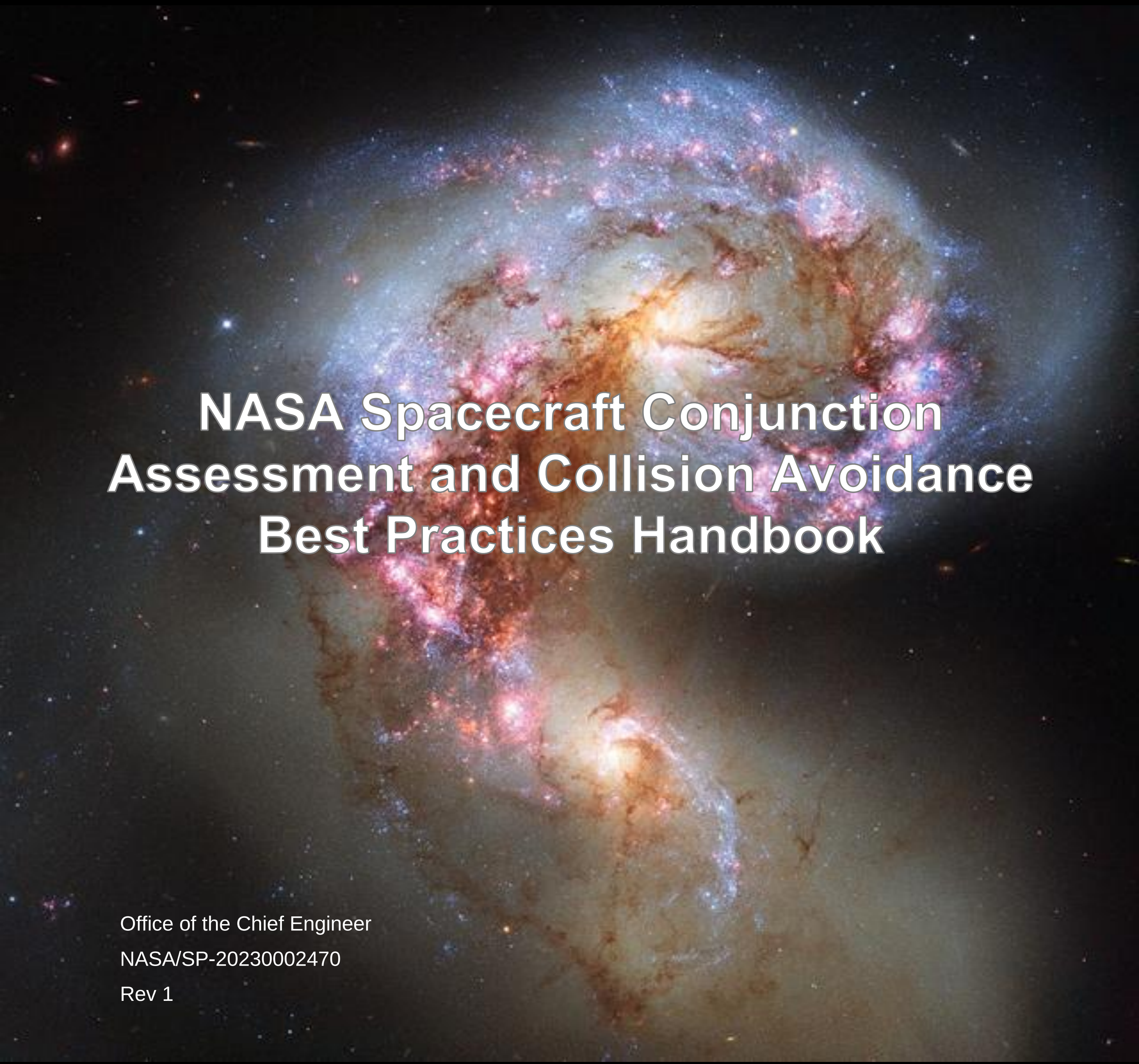
National Aeronautics and Space Administration



NASA Spacecraft Conjunction Assessment and Collision Avoidance Best Practices Handbook

Office of the Chief Engineer

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This is the first revision by the Office of the Chief Engineer of the 2020 Handbook updated to reflect the release of NPR 8079.1, *NASA Spacecraft Conjunction Analysis and Collision Avoidance for Space Environment Protection.*

The cover photo is an image from the Hubble Space Telescope showing galaxies NGC 4038 and NGC 4039, also known as the Antennae Galaxies, locked in a deadly embrace. Once normal spiral galaxies, the pair have spent the past few hundred million years sparring with one another.

Image can be found at:

https://images.nasa.gov/details-GSFC_20171208_Archive_e001327

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Preface

Since Explorer 1 was launched on January 31, 1958, the United States (U.S.) has reaped the benefits of space exploration. New markets and new technologies have spurred the economy and changed lives in many ways across the national security, civil, and commercial sectors. Space technologies and space-based capabilities now provide global communications, navigation and timing, weather forecasting, and more.

Space exploration also presents challenges that impact not only the U.S. but also its allies and other partners. 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 safer, more responsible manner. It seeks to bolster stability and reduce current and future operational on-orbit risks so that space is sustained for future generations. To this end, new and better Space Situational Awareness (SSA) capabilities are needed to keep pace with the increased congestion, and the U.S. seeks to create a dynamic environment that encourages and rewards commercial providers who improve these capabilities.

The overall purpose of the *National Aeronautics and Space Administration (NASA) Spacecraft Conjunction Assessment and Collision Avoidance Best Practices Handbook* is to equip owners/operators (O/Os) with the best practices they need to conduct their operations safely. The Handbook

- Reflects the goal of Space Policy Directive-3, the National Space Traffic Management Policy (SPD-3), to develop safety standards and best practices that consider "maneuverability, tracking, reliability, and disposal."
- Reflects how NASA currently operates in space, which evolves over time.
- Is organized around a spacecraft's life cycle. 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.
- Encourages the use of commercially available SSA data and information, and for large constellations, it encourages mitigating light pollution to ground-based astronomy.
- Focuses on current NASA best practices. It will be updated as new approaches for conjunction assessment and on-orbit operations are developed.
- Provides guidance for the requirements in NASA Procedural Requirements (NPR) 8079.1, *NASA Spacecraft Conjunction Analysis and Collision Avoidance for Space Environment Protection*.

A parallel document may be developed to highlight additional practices as the U.S. Department of Commerce develops the Open Architecture Data Repository (OADR) mandated by SPD-3. Other commercial services may be offered to supplement or replace the government services currently offered.

The approaches outlined in this document are offered to spacecraft Owners/Operators (O/Os) as an example of responsible practices to consider for lowering collision risks and operating safely in space in a stable and sustainable manner. Entities offering, or intending to offer, SSA or conjunction assessment services should consider the information in this handbook from the perspective of augmenting or improving upon existing capabilities as the entire space industry benefits from advancing these capabilities. In the near term, raw observation data can be used to improve close approach predictions. Longer-term improvements might be found in enhancing notifications and data sharing, developing new models, and enabling increased automation.

NASA continuously examines and actively updates its best practices for conjunction assessment as the industry undergoes rapid evolution. Large constellations of satellites, for example, comprise a new and evolving paradigm for which NASA is developing in-house expertise. NASA seeks input from the community to improve the content presented in this document. Comments or suggestions may be submitted to ca-handbook-feedback@nasa.onmicrosoft.com.

For space operations regulated by other U.S. agencies such as the Department of Commerce, the U.S. Federal Aviation Administration (FAA), and the U.S. Federal Communications Commission (FCC), NASA defers to those agencies. As part of interagency consultations and to contribute to safe and sustainable space operations, NASA partners such as the FAA and FCC request NASA review of license, payload, and/or policy applications made by commercial space operators to U.S. Government regulatory agencies. In addition to the information required by those regulatory agencies, NASA has prepared examples of information for various types of missions that is valuable in expediting NASA's review. Current examples can be found at https://www.nasa.gov/recommendations-commercial-space-operators. Commercial space operators are welcome to contact NASA with questions about these examples.

This document was developed in close collaboration with the U.S. Space Command (USSPACECOM), one of NASA's closest interagency partners in ensuring safe operations in space, as part of the NASA/U.S. Department of Defense (DOD) Interagency Working Group for Large Constellation Conjunction Assessment Best Practices. Special thanks are due to working group members Mr. Jeff Braxton of USSPACECOM's Strategy, Plans, and Policy Directorate, and Ms. Diana McKissock and Ms. Cynthia Wilson of the U.S. Space Force's 18th Space Defense Squadron (18 SDS).

1.0 Introduction

This document is intended to provide NASA spacecraft program and project managers, generically referred to in this handbook as O/Os, with more details on implementing requirements in NPR 8079.1 and to provide non-NASA O/Os with a reference document describing existing NASA conjunction assessment and collision avoidance practices.

Within NASA, space flight missions are typically implemented through a program/project office structure. For example, a human exploration program might involve multiple missions (i.e., discrete launches) to a common goal. In this document, the term “mission” means the end-to-end activity that results in the creation, launch, operation, and eventual disposal of a spacecraft.

This document provides detailed information on spacecraft conjunction assessment and collision avoidance topics. Best practices for each topic are described and justified throughout this document by mission phase. A summary list of these best practices without the supporting explanatory text is provided in appendices C and D. Appendix C is a complete listing of all the best practices so that non-NASA mission managers can review them to determine which are useful for their mission. The mission manager would then need to identify the person or group responsible for performing the best practice and arrange for that effort. For NASA missions, Appendix D lists the best practices and the party responsible for performing them.

Different organizations use the term “conjunction assessment” in different ways, but NASA defines a 3-step process:

1. **Conjunction assessment** (otherwise referred to as “screening”) **–** The process of comparing trajectory data from the “primary object” (the “protected asset” in NPR 8079.1) against the trajectories of the objects in the applicable database[1] and predicts when a close approach will occur within a chosen protective volume placed about the asset.
2. **Conjunction risk assessment –** The process of determining the likelihood of two space objects colliding and the expected consequence if they collide in terms of lost spacecraft and expected debris production.
3. **Conjunction mitigation** – An action taken to remediate conjunction risk including a propulsive maneuver, an attitude adjustment (e.g., for differential drag or to minimize frontal area), or provision of ephemeris data to the secondary O/O to enable that spacecraft to plan and execute an avoidance maneuver.

[1] For Earth-orbiting objects, screening is performed against the space object catalog maintained by the United States Space Command (USSPACECOM) to predict when a close approach will occur within a volume of space called a “safety volume” placed about the asset. This catalog includes information about international and commercial operational spacecraft as well as all trackable debris. For non-Earth-orbiting objects, the ephemeris of the primary (protected) asset is only screened against other provided ephemerides.

This document compiles best practices based on the U.S. Government process that exists today where conjunction assessment screening is performed by USSPACECOM/18 SDS and 19 SDS.

The risk assessment process is necessary because the orbit solutions of the catalog objects have varying accuracies depending on factors described in this document. Currently, O/Os need to perform this function for themselves (or hire a third party) because 18 SDS and 19 SDS are not tasked to perform this necessary risk assessment function. In the future, the Department of Commerce may offer risk assessment services as it takes on a space traffic management role, and broader commercial services will be available.

Some entities use Two-Line Elements (TLEs) to perform conjunction assessment. This practice is not recommended because the TLE accuracy is not sufficient to perform the necessary conjunction assessment calculations. (See Appendix E for more information on TLEs.)

The terms “satellite” and “spacecraft” are interchangeable in this document. The word “object” means any discretely identifiable debris or other cataloged item in addition to satellites and spacecraft.

The term “large constellation” is defined loosely in this document. The U.S. Government Orbital Debris Mitigation Standard Practices (ODMSP) defines “large constellation” as containing 100 or more spacecraft. However, because constellations having as few as 10-20 spacecraft can experience greater conjunction risk, the O/O of any constellation of spacecraft is asked to consider the intent of the best practices in this document and implement all of them to the degree possible.

2.0 Roles and Responsibilities

This section provides a brief introduction to the organizations referenced in this document.

The U.S. Space Command (USSPACECOM), one of the combatant commands within DOD, is responsible for U.S. military space operations. For the purposes of this document, it is the entity responsible for establishing SSA sharing agreements with domestic and international entities, both governmental and private. It establishes guidance and direction governing execution of the congressionally mandated SSA sharing program on behalf of the U.S. Secretary of Defense. It also oversees execution of the SSA sharing program as well as day-to-day operations of the USSPACECOM SSA and space flight safety support.

The U.S. Space Force's 18th and 19th Space Defense Squadron (18 SDS and 19 SDS) maintain the U.S. catalog of space objects and provide 24/7 space flight safety support on behalf of USSPACECOM. 18 SDS conducts advanced analysis, sensor optimization, human space flight support, reentry/break-up assessment, and launch analysis; 19 SDS conducts conjunction assessment and launch conjunction assessment.

The NASA Human Space Flight Operations Directorate (FOD) of the Johnson Space Center (JSC), through the console positions Trajectory Operations Officer (TOPO) and Flight Dynamics Officer (FDO), provides conjunction risk analysis support to the space flight missions that fall under NASA human space flight. The International Space Station (ISS) and vehicles visiting the ISS receive conjunction risk assessment support from the TOPO,[2] while Artemis space flight missions receive conjunction risk assessment support from their assigned FDO. The TOPO group is the sole liaison to USSPACECOM and the U.S. Space Force for matters related to trajectory maintenance and the orbital safety of human space flight assets.

The NASA Conjunction Assessment Risk Analysis (CARA) Program located at the Goddard Space Flight Center (GSFC) provides conjunction analysis and risk assessment services for all NASA spacecraft not affiliated with human space flight. CARA is responsible for protecting the orbital environment from collision between NASA non-human space flight missions and other tracked and cataloged on-orbit objects. CARA is responsible for routinely collecting predicted orbital information from NASA spacecraft operators, passing it to NASA Orbital Safety Analysts (OSAs) for screening against the space object catalog, analyzing the screening results to determine the risk posed by predicted close approaches, and working with NASA spacecraft operators to determine an appropriate mitigation strategy for the risks posed by close approaches. CARA is the sole entity with authority to submit Orbital Data Requests (ODRs) to DOD on behalf of NASA non-human space flight entities in accordance with NPR(8715.6, *NASA Procedural Requirements for Limiting Orbital Debris and Evaluating the Meteoroid and Orbital Debris Environments*. CARA is the designated point of contact between NASA and USSPACECOM and the U.S. Space Force for matters related to trajectory maintenance and orbital safety of non-human space flight assets.

[2] However, for missions deployed from ISS or visiting vehicles, JSC FOD certifies that the mission has a conjunction assessment process as outlined in jettison policies but does not provide direct conjunction risk assessment support.

3.0 Conjunction Assessment: Past, Present, and Future

This section provides a brief history of the conjunction assessment function, including an overview of who the actors are and why the activities are arranged as they are. It explains why the conjunction assessment and related safety-of-flight services currently available exist in their present forms and how they are evolving to accommodate new requirements.

3.1. Origins

The present conjunction assessment process, which predicts close approaches between space objects, began in support of the NASA Space Shuttle Program return-to-flight effort after the Challenger accident in 1986. Drawing on the DOD's ability to track space objects for missile defense and SSA, the two U.S. Government entities partnered to expand the capability to offer a methodology that would protect humans in space.

What most people consider the "space catalog" is a database of TLE sets that permits a medium-fidelity propagation and orbit prediction of all tracked objects larger than approximately 10 cm in Low Earth Orbit (LEO) using Simplified General Perturbation Theory #4 (SGP4).[3] The satellite catalog was originally designed not for conjunction assessment but for generalized space safety, predicting the location of objects with sufficient accuracy for sensors in the network to reacquire those objects, thereby maintaining custody for purposes such as ensuring that intercontinental ballistic missile threats could be differentiated from satellites in orbit. The catalog was then, and is today, maintained using the radars, telescopes, and other sensors comprising the Space Surveillance Network (SSN). In recent years, however, USSPACECOM has been working to augment the existing network by incorporating observations from international and commercial entities.

For ISS conjunction assessment to better protect humans in space, NASA collaborated with the U.S. Air Force to develop an improvement to the TLE catalog that would be accurate enough to compute a Probability of Collision (Pc) between two objects. To compute Pc, orbit determination covariance data were needed. Since the general perturbations theory used to maintain the TLE catalog (SGP4) did not produce a usable covariance, the current Special Perturbations (SP) Space Object Catalog was developed. 18 SDS, the U.S. Space Force unit that currently maintains the catalog at Vandenberg Space Force Base (VSFB) on behalf of USSPACECOM, 18 SDS at VSFB, California and 19 SDS at Dahlgren Naval Base, Virginia have greatly expanded the process of screening protected assets since that time (especially since the Iridium 33/COSMOS 2251 collision in 2009) to include all operational assets currently on orbit.

However, since the process was developed 50 years ago and was grown piecemeal to meet existing needs, it contains certain oddities of evolution that may not be anticipated by O/Os who are accustomed to using current technology and methods. Understanding how the 18 and 19 SDS process works is key to using it properly to protect on-orbit assets and the space environment.

[3] Hoots and Roehrich 1980.

3.2. USSPACECOM Conjunction Assessment Process

The full conjunction assessment screening process used by USSPACECOM with all accompanying details is documented in the *Spaceflight Safety Handbook for Satellite Operators* (the Spaceflight Safety Handbook), which can be obtained along with other helpful information from the USSPACECOM website space-track.org. This website is the principal way USSPACECOM communicates and exchanges conjunction assessment-related information with O/Os.

- All non-NASA spacecraft O/Os should familiarize themselves with the Spaceflight Safety Handbook as well as other website contents and offerings.
- NASA spacecraft O/Os do not need to be familiar with the Spaceflight Safety Handbook since CARA or JSC FOD will perform all actions on their behalf.

(See Section 7 in this document for USSPACECOM contact information including Uniform Resource Locators (URLs) to obtain products. See Sections 5.1 through 5.3 for details of some topics from the Spaceflight Safety Handbook to provide end-to-end understanding of the conjunction assessment process.)

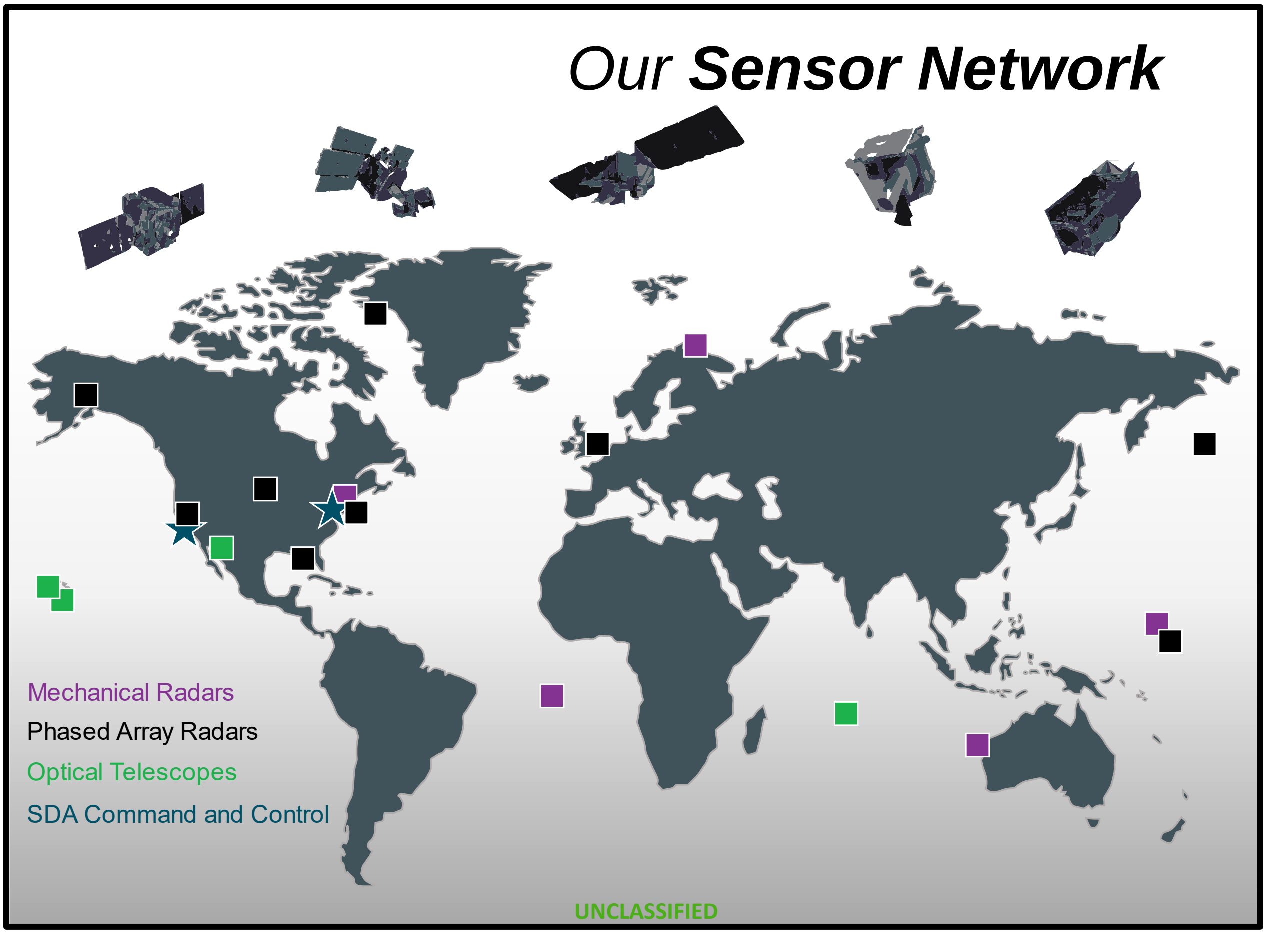
Commercial conjunction assessment providers, often using space catalogs assembled from private sector space tracking assets, are now an available resource for O/Os who wish to obtain conjunction assessment services. NASA encourages the use of validated commercial conjunction assessment services when they can augment the existing USSPACECOM capabilities. NASA recommends that all O/Os avail themselves of the USSPACECOM conjunction assessment service at a minimum as an adjunct to a commercially procured service. (See Section 6.1 for additional information about orbital data for conjunction assessment; Appendix J, which outlines conjunction risk assessment tools validation procedures; and Appendix L, which addresses the question of the use of commercial SSA data in conjunction risk assessment.)

To address this topic, the following specific practices are recommended:

A. Obtain a space-track.org account.
B. Become familiar with the Spaceflight Safety Handbook contents.
C. Use USSPACECOM conjunction assessment service as a minimum for screenings, even if additional commercial data or services are used.

3.2.1. SSN Tracking Functionality Description

The Space Surveillance Network (SSN), a global sensor network made up of optical telescopes and radars, is used to collect the tracking observations that are processed to maintain the High Accuracy Catalog (HAC) of on-orbit space objects. Figure 3-1 shows the current locations of the member sensors.



SDA = Space Domain Awareness

Figure 3-1 Locations and Types of SSN Sensors and Nodes[4]

Because most sensors have other purposes in addition to collecting data for SSA, tracking data cannot be simply requested and obtained on demand. Objects are placed in tasking categories, and a list of objects to attempt to track by category is sent to each sensor, which then sorts the list to determine which requests are feasible given the sensor's calculation of the probability of detection of the requested satellite and competing activities.

Priority is given to military operational needs and special needs within conjunction assessment such as human space flight. If a USSPACECOM conjunction assessment operator determines that there is insufficient tracking data available to create a good orbit determination solution for an object, the operator may attempt to obtain additional data by increasing the priority of the object or by tasking additional sensors to track it. Sensors may not be able to track an object due to geometric and power constraints, weather, equipment outages, and other exigencies.

[4] Figure courtesy of USSPACECOM.

The USSPACECOM process is different from a commercial process in which a vendor is compensated directly for the tracking of an object with the flexibility of being able to obtain additional data if more funds are available to support the request. Because of the time required to collect additional data on an object of concern using the USSPACECOM process, it is recommended that O/Os provide a significant length of ephemeris prediction (including planned maneuvers) to USSPACECOM for screening. This screening duration allows time for USSPACECOM conjunction assessment operators to increase tasking for identified secondary objects with insufficient orbit determination solutions, and thus to enable the best Pc to be computed for use in conjunction risk assessment decisions. (See Section 6.1 for a more detailed discussion of these issues.)

To address this topic, the following specific practice is recommended:

A. Provide seven (7) days of predicted ephemeris (including maneuvers) to USSPACECOM for screening for LEO spacecraft, and provide 14 days for other Earth orbits; e.g., High Earth Orbit (HEO)/Geosynchronous Orbit (GEO).

3.2.2. USSPACECOM Conjunction Assessment Screening Timeline and Process

Personnel at the USSPACECOM facility at Dahlgren Naval Base currently perform screenings of protected assets against the entire HAC once per day at a minimum and up to three times per day every day. Screenings are performed using both the ephemeris data that O/Os share (which include planned maneuvers for the asset) as well as the SSN-derived orbit determination solution for the asset (which does not consider predicted maneuvers).

Results from the screenings, in the form of Conjunction Data Messages (CDMs), are posted to space-track.org for customers with accounts. Entities without accounts who have provided an email address to USSPACECOM may receive basic prediction information by email if an emergency is detected.

Special/off-cycle screenings can be requested per the guidance in the Spaceflight Safety Handbook. It is important for safety of flight for all spacecraft operators to ensure that there are no large latencies or gaps in the process as uncertainties in the propagated orbit continue to grow over time. For instance, submitting an ephemeris for screening today at noon that has an epoch of today at 0 hours means that the data is already 12 hours old. If it then takes 8 hours to screen that data and another 2 hours to analyze the results, the data will be very old indeed. Ensure that the data screened is for a future time and is analyzed and acted upon before it becomes stale. (See Section 6.2 for more information.)

To address this topic, the following specific practices are recommended:

A. Provide at least one ephemeris per day to be screened and three ephemerides per day in the lower-drag LEO regime (perigee height less than 500 km).

B. Determine whether the O/O's process for obtaining screening results and performing conjunction risk assessment aligns with the timeline of the USSPACECOM process. If the timelines do not align in such a way as to enable timely and efficient screening support, pursue a rearrangement of the O/O's process to minimize data latency and optimize screening efficiency.

3.2.3. Data Sharing with Other O/Os

To facilitate communication between operators to mitigate a close approach, USSPACECOM maintains a list of contacts for each asset. Maintaining this list of contacts is critical so that someone can always be reached. Data sharing is further facilitated though the use of standard formats and coordinate frames. (See Section 6.4 for a more thorough treatment.)

To address this topic, the following specific practices are recommended:

A. Populate and maintain the point of contact section on space-track.org with your operations contact data. Be sure that the operations contact can be reached 24/7 due to time zone differences between operators and the immediate nature of certain conjunction assessment emergencies.

B. Use standard ephemeris, CDM, and maneuver notification formats defined by the Consultative Committee for Space Data Systems (CCSDS).

3.2.4. SSA Sharing Agreements

USSPACECOM/J535, SSA Data Sharing Branch, negotiates SSA sharing agreements, which establish the parameters within which data will be exchanged by the signing parties to facilitate ongoing cooperation and advance space flight safety. These agreements are useful because they substantially expand the types of data products that can be received over the default products provided to entities without agreements.

Any member of the space community, including satellite operators, launching agencies, commercial service providers, and research/academic institutions, that wishes more and more frequent SSA products than are provided through a generic space-track.org account should contact USSPACECOM. (See Section 7 of this document for contact information.)

U.S. Government organizations and their contractors have implied agreements and do not need to pursue a separate formal arrangement with USSPACECOM.

3.3. NASA Partnership with USSPACECOM

Since the development of the HAC and its use in routine conjunction assessment screenings, NASA has partnered with USSPACECOM and its predecessor organizations. That partnership currently includes special, dedicated conjunction assessment screening support. The human space flight program uses U.S. Air Force civilians for conjunction assessment screening support, while NASA's non-human space flight missions are supported by NASA contractors called Orbital Safety Analysts (OSAs) who work on the operations floor in the VSFB operations center. While both groups do essentially the same work with the same input data, NASA OSAs focus specifically on NASA needs and can write scripts that are used to tailor the output data for use by CARA.

Conjunction assessment is a 3-step process:

1. The first step is conjunction assessment "screening," which involves computing the predicted close approaches between the protected asset and the catalog of space objects. This is the step performed at the USSPACECOM facility for mission customers, and screening results are provided that describe predicted close approaches. Both the USSPACECOM conjunction assessment cell and NASA OSAs perform this function.
2. The second step is conjunction "risk assessment," in which the screening results are analyzed to determine the level of risk posed by each predicted close approach and to determine whether the predicted close approaches warrant additional investigation and, ultimately, mitigation. This step is critical because not all predicted close approaches require mitigation, and often close approaches require analysis to determine what action is warranted. This step is not performed by USSPACECOM as it is a responsibility allocated to O/Os or organizations that perform this activity on the O/O's behalf. NASA JSC FOD performs this function for human space flight program assets, and NASA CARA performs this function for all other NASA spacecraft.
3. The third step, if required, is conjunction "mitigation," in which the O/O plans, and perhaps executes, a collision avoidance maneuver or other mitigation solution to reduce the collision risk to an acceptable level. This activity is allocated to the individual O/Os although NASA CARA does provide some basic support tools to aid in the initial choice of mitigation actions for its mission customers.

Because risk assessment requires different products and yields different analyses than screening, it is important to consider the tools and processes required to assess risk properly and adequately. For large constellations, the cadence of conjunctions and the consequence of a collision for the proper operation of the constellation are both heightened. (See Section 6 for more detail on risk assessment processes.)

To address this topic, the following specific practices are recommended:

A. Develop a robust safety-of-flight process that includes both conjunction assessment screening and risk assessment to inform close approach mitigation decisions.

B. Large constellation operators should work with USSPACECOM pre-launch to determine if variations from the standard approach are necessary and, if so, to define a tailored screening process.

C. Large constellation operators should consider working with NASA to define a risk assessment process. NASA is an experienced representative operator. Including NASA in discussions regarding establishing a conjunction assessment process will ensure that the process will work with most operators for risk assessment purposes.

3.4. Conjunction Assessment in Cislunar Space

Significant investments by the U.S., China, other nations, and commercial companies in missions to cislunar space between Earth and the Moon have highlighted the need for proper measures to ensure the safety of the space environment in that regime. While cislunar space will remain "big" for some time yet, popular locations and transit trajectories are likely to experience rapid growth, requiring effective conjunction risk analysis to maintain safety. Implementing appropriate measures for spacecraft will ensure readiness to perform effective conjunction risk assessment as cislunar space traffic increases.

In November 2022, the White House National Science & Technology Policy Council released the National Cislunar Science & Technology Strategy, an interagency strategy to guide developments across a spectrum of emerging areas in the cislunar "ecosystem" (National Cislunar Science & Technology Strategy, 2022). Several objectives espoused in this document pertain to Space Situational Awareness (SSA) and space safety, including the following:

- Develop technical foundations of best practices for safe cislunar space flight operations.
- Develop an integrated cislunar object catalog.
- Develop procedures for publicly sharing cislunar SSA data as well as navigation and space flight safety support in cislunar space.
- Ensure that capabilities for U.S. Government cislunar operations are scalable and interoperable with systems operated by private and international actors.

(For additional details and context, refer to the Strategy document.)

3.4.1. Key Goals

For the purpose of outlining best practices for conjunction risk assessment, key goals center on sharing data and ensuring interoperability. These goals can be achieved through the delivery of standardized file formats and content, along with the use of consistent trajectory models and coordinate frame definitions.

The use of consistent trajectory models and coordinate frame definitions is best realized by conforming to the recommendations in the recently released NASA Technical Publication "Astrodynamics Convention and Modeling Reference for Lunar, Cislunar, and Libration Point Orbits" (Folta et al. 2022). This document details coordinate and time systems, numerical integration techniques, and trajectory modeling of three-body systems at different levels of fidelity appropriate for mission design and navigation of spacecraft well beyond geosynchronous orbit (GEO). A cislunar conjunction risk assessment best practice is to conform to the astrodynamics conventions and modeling recommendations of this NASA technical publication to enforce consistency across ephemerides from different sources, thereby enabling more accurate conjunction assessments.

The goal of standardizing file formats and content has been addressed by DOD, NASA, and academia through a Cis-Lunar SSA Technical Steering Group led by the National Geospatial-Intelligence Agency (NGA). The Steering Group has produced a draft document outlining an enhanced message set that enables communication of space object catalog and observational data for the cislunar regime (Butt 2021).[5] The recommended set covers object state and covariance information in the catalog content message and sensor observations in the tracking data message. These formats overcome shortcomings of the current SSA message set that prohibits accurate expression of cislunar data and also update features of the current set that have not evolved with advances in SSA since their inception in the 1960s.

A cislunar conjunction risk assessment best practice is to conform to these recommendations when developing SSA architectures to support cislunar missions.

3.4.2. Conjunction Screening Process

Sharing of standardized ephemeris and covariance data is the intent of the current practice of Earth orbiter owner/operators (O/Os) delivering files to conjunction screening providers such as the U.S. Space Force 18th Space Defense Squadron (18 SDS), 19th Space Defense Squadron (19 SDS), or CARA for use in computing a probability of collision (Pc) during encounters. However, cislunar conjunction assessment currently has no catalog of cislunar objects with independent trajectory and covariance solutions and so requires a different screening process.

NASA currently performs conjunction assessment around Mars, the Moon, and Sun/Earth libration points through the Multimission Automated Deepspace Conjunction Assessment Process (MADCAP) based at the Jet Propulsion Laboratory (JPL). More information about MADCAP and related processes is available on the organization's website: https://www.nasa.gov/cara/madcap and in the document Tarzi et al. 2022. Spacecraft operators, including for non-NASA and even non-partner international spacecraft, deliver ephemerides to the NASA Deep Space Network (DSN) Service Preparation Subsystem (SPS) portal, through

[5] https://www.nasa.gov/sites/default/files/atoms/files/cislunar_ssa_proposed_message_set-nov2021_rev2_without_emailspdf.pdf

which MADCAP can access them. MADCAP assesses conjunction risk based on Pc if a covariance is provided, or (if necessary) via typical radial and timing prediction uncertainties provided by the respective mission navigation teams. These uncertainties are fit to polynomials in time and mapped to the relative node of the two orbits to assess the risk of collision at the crossing. However, as described in Tarzi et al. 2022, MADCAP has implemented the capability to compute two-dimensional Pc (2D-Pc) when given ephemerides with covariance. When potentially risky conjunctions are discovered, notifications and conjunction event data are forwarded to both satellites' operations teams, who then are expected to work with each other to determine if a mitigation action is necessary and, if so, execute it. JPL's MADCAP Team will facilitate the decision process if the operations teams cannot agree on a course of action.

Regarding the lack of a centralized catalog of cislunar objects, that is currently in work by 19 SDS. In fact, many cislunar conjunction assessment capabilities are evolving with the potential for significant advances in deep space tracking, trajectory modeling, and ephemeris sharing interfaces. Because many of these advances are still in development, the baseline for conjunction risk assessment must rely on ephemeris and covariance produced by the O/O rather than catalog screening.

As such, the O/O should deliver a CCSDS Orbit Ephemeris Message (OEM) formatted ephemeris with covariance to both space-track.org and to the DSN SPS portal. This will allow access to the trajectory and its uncertainty for screening by both 19 SDS (through SpaceTrack) and MADCAP (through SPS).

The CCSDS format is the current industry standard, aligning with the standardization goal outlined above. Because a non-cooperative orbit solution for cislunar spacecraft is not currently available, inclusion of the covariance in the O/O ephemeris file is essential to allow computation of the probability of collision. Establishing the best practice of O/Os providing accurate trajectory and covariance for their spacecraft in cislunar space to current ephemeris interfaces sets the stage for effective conjunction screenings as operational advances continue to be made in the cislunar regime.

To address this topic, the following specific practices are recommended:

A. Owner/operators should conform to recommendations in the NASA Technical Publication "Astrodynamics Convention and Modeling Reference for Lunar, Cislunar, and Libration Point Orbits."

B. Cislunar mission support entities (sensors, catalog maintainers, etc.) should conform to the enhanced SSA message set (Butt 2021) when creating cislunar SSA architectures.

C. Owner/operators should maintain accurate orbit determination solutions and predicted covariance for objects in cislunar space.

D. Owner/operators should deliver predicted ephemeris with covariance in the CCSDS format to space-track.org and to the DSN SPS portal.

4.0 Spacecraft and Constellation Design

Safety of flight is an integral aspect of satellite space operations and should be considered as part of design decisions to enable cost- and mission-effective solutions so that potential impacts to other operators in the space environment can be avoided. Specific design areas for which the consideration of on-orbit safety issues is appropriate include:

- orbit selection,
- spacecraft ascent and disposal activities,
- sensor trackability of the spacecraft,
- spacecraft reliability,
- capabilities for ephemeris generation, and
- capabilities for risk assessment and mitigation.

Each of these items is treated in more detail in this section.

4.1. Ascent to/Disposal from the Constellation's Operational Orbit

Safety-of-flight issues may be considerable when related to the ascent from the launch injection point to the satellite's on-station position or to the descent to an orbit from which disposal/re-entry can be accomplished directly. Typical ascent and descent trajectory design using now common electric propulsion or low-thrust chemical propulsion can take months to accomplish, potentially passing through highly populated regions of space along the way. For large constellations, the amount of nearly continuous transiting satellite traffic could be especially large as old satellites pass out of service and replacement satellites are added.

All missions should plan for orbit disposal to reduce long-term orbital debris. Reducing the number of inactive space objects minimizes the probability of generating debris through orbital collisions, and the fastest disposal option should be pursued; for example, existing large constellations are promptly deorbiting end-of life spacecraft. The U.S. Government has established Orbital Debris Mitigation Standard Practices (ODMSP) including for post-mission disposal.[6] NASA missions are required by NPR 8715.6 to comply with NASA Standard 8719-14B, *Process for Limiting Orbital Debris*, which defines how NASA implements the ODMSP.

During ascent and descent, a spacecraft will pass by other assets that are already on orbit. Some but not all of those may be maneuverable. The ascending/descending spacecraft that is equipped to maneuver needs to yield the right-of-way to existing on-orbit assets by performing risk mitigation maneuvers or ascent/descent trajectory alterations.

Special caution is needed to protect humans on orbit. If the ascent or descent trajectory will pass through the ISS altitude, operators should coordinate with the NASA JSC FOD to avoid perigee-lowering approaches that pose persistent and problematic orbital crossings with ISS and other human space flight assets.

[6] U.S. Government Orbital Debris Mitigation Standard Practices. 2019 version https://orbitaldebris.jsc.nasa.gov/library/usg_orbital_debris_mitigation_standard_practices_november_2019.pdf.

To address this topic, the following specific practices are recommended:

A. Perform a study to compute the number of expected close approaches anticipated during ascent and descent as well as the imputed additional satellite reliability that will be required to meet satellite disposal requirements at the chosen operational orbit.

B. If the results of the study show a large burden, consider choosing a different mission orbit with a lower burden.

C. All missions should review and follow the ODMSP guidance standards.

D. When practicable, pursue active disposal using the fastest disposal option available.

E. Recognize that transiting spacecraft should yield way to on-station spacecraft and thus take responsibility for any conjunction risk mitigation maneuvers or transient trajectory alterations that may be required.

F. When planning descent using thrusters, if not planning an approach of circular-orbit altitude reduction, coordinate with the NASA JSC TOPO to ensure that perigee-lowering approaches do not present persistent and problematic orbital crossings with the ISS and other human space flight assets.

4.2. General Orbit Selection: Debris Object Density

Space debris is not uniformly distributed about the Earth. Because most of the present space debris is generated from a relatively small number of satellite collisions or explosions, the orbital parameters of these collided or exploded satellites determine where the large debris fields reside.

For example, the debris object density is much greater in the 750-900 km altitude band than in other parts of LEO. If possible, this region is one to avoid as a destination orbit since a larger number of serious satellite conjunctions with debris objects can be expected. An orbit that results in a high number of close approaches can lead to the need to perform many maneuvers that may not fully mitigate the risk of close approach. Spacecraft that cannot maneuver will operate at higher risk of debris creation, effectively presenting additional risk to other operators.

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 permit the number of desired years on orbit. Published results by NASA CARA are available and can be consulted to obtain first-order high-interest event density information. (See Appendix F for more information and examples.) Use this information to assess the mission impact for conjunction risk mitigation maneuvers, given the expected lifetime of each satellite (e.g., additional propellant required, impacts on data collection).

To address this topic, the following specific practices are recommended:

A. Include considerations of orbital debris density when selecting candidate mission orbits. Debris density diagrams, indexed by object size, are published by the NASA Orbital Debris Program Office (ODPO). (See Appendix G for more information and examples.)
B. When choosing from the final set of candidate orbits, perform a conjunction frequency analysis to determine the number of conjunction high-interest events per spacecraft per year that can be expected in each of the proposed orbital areas.

4.3. Vehicle- and Constellation-Specific Orbit Selection: Spacecraft Colocation

While there is a process used by the International Telecommunication Union (ITU) to ensure that spacecraft locations are deconflicted from a radio frequency perspective, there is no similar centralized process for ensuring that spacecraft locations are deconflicted from a location perspective. This gap has resulted in spacecraft injecting into their planned mission orbit only to find another spacecraft already in or very near that location (colocated), which causes close approaches that then have to be mitigated, potentially very frequently, over the whole mission lifetime.

Another similar problem is that of systematic or repeating conjunctions in which a spacecraft has multiple repeated close approaches on successive orbits with another object over a long period of time; for example, when using electric propulsion to move slowly through a congested area. Two actively maintained spacecraft with very similar orbits can present a permanent recurring collision hazard because both spacecraft can be planning future maneuvers that result in a collision if not coordinated. Therefore, active coordination for every maneuver is required to prevent the execution of simultaneous maneuvers that could create a collision.

Due to the lack of centralized coordination, it is incumbent upon individual operators to protect themselves and the space environment by performing their own colocation analysis. The goal would be to prevent choosing a location already occupied by another spacecraft, or, if that is not possible, to work with the other operator before launch to devise a strategy to share the space. Colocation situations can often be ameliorated through relatively small changes to the planned orbits during the design phase. For NASA missions, CARA can perform this analysis using the current USSPACECOM catalog data. (See Appendix H for more information and examples.) For non-NASA missions, CARA will make their software tool available via public release.

In performing the analysis, it is not necessary to consider proximity to objects that are not maneuverable (debris, rocket body, dead spacecraft) since the non-maneuverable object will pass through the area under the control of non-conservative forces such as atmospheric drag and not present a future issue for the (largely) static orbital parameters of the asset that is maintaining its orbit using maneuvers.

To address this topic, the following specific practices are recommended:

A. During orbit selection, perform an orbit colocation analysis to determine whether any of the proposed orbits is likely to create systematic conjunctions with existing actively maintained satellites.

B. If the orbit colocation analysis identifies systematic conjunctions, consider modifying the proposed orbit(s) slightly to eliminate this possibility. Optimizing orbit placement may be appropriate.

C. If the selected orbit is likely to present systematic conjunctions with a pre-existing spacecraft, then coordinate with the other operator(s) to arrange a process to coordinate maneuver plans routinely during the life of the mission.

4.4. Launch-Related Conjunction Assessment

Launch Collision Avoidance (Launch COLA or LCOLA) is the evaluation of a particular launch trajectory to determine whether the launch assembly, following this trajectory, will produce any close approaches with other space objects. LCOLA is sometimes expanded to include more indirect analyses to ensure that launch offscourings (rocket bodies, fairings, etc.) do not produce close approaches with other objects during the first three days after launch, after which they can be presumed to be cataloged and thus handled by the usual on-orbit conjunction assessment methods.

LCOLA requirements are governed by the individual launch range or launch licensing agency. Requirements are in the form of stand-off distances Pc depending on whether the on-orbit conjuncting asset is a piece of debris, operational payload, or human space flight mission. Examples of the current requirements are 200 km stand-off distance or 1E-6 Pc between the object to be launched and human space flight assets and 25 km or 1E-5 Pc between the object to be launched and non-human space flight operational payloads. In practice, LCOLA covers launched objects from the time they reach 150 km through three hours. Launch times found in violation of these requirements are enforced as launch hold periods by the respective wing commanders.

A large study conducted by NASA (Hejduk et al. 2014) questioned the added value of LCOLA, given the uncertainties typical of most predicted launch trajectories. However, recent improvements in the fidelity of these predicted trajectories have made the LCOLA enterprise potentially more meaningful, suggesting that the situation may need to be reevaluated.

The period between when traditional LCOLA ends and when an on-orbit asset can mitigate a risk using standard on-orbit conjunction assessment methods is called the COLA gap. The O/O should ensure that newly launched objects and their detritus will not come into conjunction with protected assets during the COLA gap (i.e., until the 18 and 19 SDS can catalog the new object(s) so it is available for conjunction assessment screening). Such analyses should consider not just the predicted nominal launch injection but the expected (up to three-sigma) launch dispersions.

Specific criteria defining COLA gap launch cutouts do not exist since they are dependent on both what is being launched and the capabilities of the protected on-orbit asset. For example, ISS needs 36 hours for the COLA gap, which allows 24 hours for 18 and 19 SDS to track the launch objects and then 12 hours for ISS to assess the risk and mitigate if required. Other assets might require more time to close this risk gap. The methodology for this risk assessment can be a stand-off distance phasing analysis, nodal separation and in-track screening, or a probability density model. Note that this analysis is typically performed by Aerospace[7] for DOD missions and the NASA Launch Services Program for NASA missions. These organizations can be consulted for details on the analysis techniques and criteria, which are also listed in Appendix Q (Hametz and Beaver 2013; Jenkin et al. 2020). NASA JSC FOD can also be consulted for analysis methods and to obtain details on the assets that could be at risk for each specific launch.

To address this topic, the following specific practices are recommended:

A. Protect human space flight assets from close approaches during the COLA gap using stand-off distance or statistical measures.

B. Conform to additional LCOLA requirements that the launch range may impose.

4.5. Spacecraft Trackability

Effective conjunction assessment requires an accurate orbital state. Accurate orbital state data requires tracking data to maintain a comprehensive space catalog available to all space operators. The USSPACECOM catalog serves this purpose and uses the data collected by the SSN. Because even active spacecraft become debris after their end-of-life and therefore need tracking to obtain an orbit solution, all launched satellites need to be acquirable and trackable by the SSN from deployment until their demise so that they can be cataloged and maintained using SSN capabilities alone. Launching an untrackable spacecraft increases risk to all operators.

Objects are trackable if they have a large enough radar or optical cross section to be tracked by at least two SSN sensor assets. Analytical evaluations of trackability consider both object size and material properties, so there is no absolute size threshold that is determinative. But as a rule of thumb, satellites need to have characteristic dimensions 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.

If a satellite exceeds the above dimensions, then there is a reasonable expectation of its being tracked by the existing SSN, and typically no further concern with trackability is needed. If a satellite is smaller than the above dimensions, then additional arrangements should be made to see to its orbital maintenance should its onboard navigation fail. Such arrangements could include an agreement with a commercial SSA company to provide tracking and construct a predicted ephemeris until re-entry or to add a trackability enhancement or autonomously powered beacon device to allow the satellite’s position to be determined for the whole of its

[7] Aerospace is an independent, nonprofit corporation operating the only Federally Funded Research and Development Center (FFRDC) for the space enterprise.

orbital life. For objects that will regularly occupy a large number of altitudes, such as a HEO object, special examination of the situation is required. For example, the object might be trackable at the lower altitudes but not the higher ones, and the orbit might be eccentric enough and with low enough perigee that good orbital modeling will require tracking at both apogee and perigee; in such a case, the larger spacecraft dimension would need to be met to guarantee trackability along the whole of the orbit.

To address this topic, the following specific practices are recommended:

A. Through selection of physical design and materials, ensure that the satellite is trackable by SSN from deployment until demise.
    a. For spacecraft with perigee heights less than 2000 km, the spacecraft should have characteristic dimensions of at least 10 cm in each major dimension.
    b. For spacecraft with perigee heights greater than 2000 km, the spacecraft should have characteristic dimensions of at least 50 cm in each major dimension.
    c. If the spacecraft cannot meet these dimension constraints, use a proven detectability enhancement.
    d. For spacecraft having orbits that span a large range of altitudes, ensure that the spacecraft is trackable at all altitudes.

4.6. Spacecraft Reliability

Studies related to active debris removal strategies have shown that the greatest contributor to long-term space debris growth is derelict spacecraft left on orbit. Such spacecraft produce opportunities for collision with smaller debris objects that cannot be mitigated, which will then generally produce large amounts of debris. So, it is important to ensure that spacecraft survive until they can be disposed of by using appropriate disposal as described in the OMDSP and by ensuring that the probability of successful post-mission disposal meets or exceeds 99%.

To address this topic, the following specific practices are recommended:

A. Ensure that spacecraft reliability is high enough that the likelihood of each spacecraft remaining fully functional until it can be disposed of meets or exceeds 99%.

B. Reassess the 99% analysis whenever the underlying assumptions change; for example, extending operations beyond design life or failures in key systems.

4.7. Development of Capabilities for Ephemeris Generation and Conjunction Risk Assessment and Mitigation

Conjunction assessment capabilities are needed immediately after launch. The software and process components of the conjunction risk assessment and mitigation capabilities should be fully developed and tested before launch including elements of both the flight hardware and the ground system.

Three main capabilities should be developed:

1. **Predicted ephemeris capability.** Predicted ephemeris data that can be shared with other O/Os is needed to assess the potential for collisions between space objects. The current U.S. Government conjunction assessment process uses two predicted ephemeris solutions for the asset: one generated using non-cooperative SSN tracking data and one shared with 18 and 19 SDS by the O/O. For active, maneuverable spacecraft, the O/O-generated ephemeris is often the best representation of the future position because the O/O usually has access to more cooperative tracking data to feed the orbit-determination process (for example, from onboard Global Positioning System (GPS) receivers); has an accurate model of the spacecraft's drag coefficient and frontal area; and, most importantly, can model planned future maneuvers in the predicted trajectory. To enable the conjunction assessment process, predicted ephemerides must be furnished frequently, span an appropriate period of predictive time, employ point spacing close enough to enable interpolation, provide a full state (position and velocity) for each ephemeris point, and provide a realistic 6 x 6 covariance matrix (with both variance and covariance terms) for each ephemeris point. (See Appendix I for more details about covariance realism characterization and evaluation.)
2. **Risk assessment capability.** The results of satellite conjunction screening analyses are sent from USSPACECOM to O/Os in the form of CDMs that contain the states, covariances, and amplifying orbit determination information for the primary and secondary object at the Time of Closest Approach (TCA). These messages, however, are only a notification of a predicted potential close approach. For a robust safety-of-flight process, additional risk assessment analysis is needed to determine whether the close approach warrants mitigation. Conjunction risk assessment tools are needed to perform this risk assessment, which includes calculation of Pc and other relevant information such as expected collision consequence (addressed in Appendix O) and whether the state and covariance information is sufficiently accurate to subtend the risk assessment process (addressed in Appendix P). For conjunction events in which the Pc exceeds a severity threshold, mitigation action planning is necessary to plan a mitigation option that will lower the Pc to below an acceptable threshold, usually conducted with the aid of trade-space plots that give conjunction Pc reduction as a function of spacecraft trajectory modification size and execution time. Validating these tools is important well before flight. (See Appendix J.) Some commercial vendors offer risk assessment services. Spacecraft operators who choose to purchase risk assessment services should make these arrangements well before launch to ensure adequate time for testing and development of a corresponding process for choosing a mitigation option given the risk assessment results received from the service.
3. **Mitigation capability.** A spacecraft can mitigate a close approach in several ways:
    - Propulsive maneuvers (e.g., performed using thrusters).
    - Attitude changes to take advantage of altered drag coefficients from altered frontal areas to effect a relative velocity change between the two objects.

- Changing the spacecraft attitude to present a minimal frontal area to the relative velocity vector to minimize the likelihood of collision.
- Sharing ephemeris data with the operator of the other spacecraft involved in the close approach so that they can perform an avoidance maneuver.

Because the design of the spacecraft and/or ground system needs to accommodate the ability to perform these actions, spacecraft operators should choose a mitigation option when they select their mission orbit and ensure that the capability is built into the system appropriately in time for testing and use.

To address this topic, the following specific practices are recommended:

A. Develop and implement a capability to generate and share accurate predicted spacecraft ephemerides including any planned maneuvers. (See Section 3.1 for a discussion of ephemeris sharing for screening. See Section 6.2 for specific guidance on ephemeris generation frequency, length, point spacing, formatting, and contents.)

B. Determine during spacecraft design what risk mitigation approaches are possible for the spacecraft. While trajectory modification via thrusting maneuver is the most common approach, other approaches such as differential drag orbit modification are possible.

C. Develop and implement or arrange to acquire a capability to process CDMs and to compute conjunction risk assessment parameters such as the Pc.

D. Develop and implement or arrange to acquire a risk analysis capability to select mitigation actions that will lower the Pc for dangerous conjunctions to a user-selected value.

E. Validate conjunction assessment tools well before flight, typically 6-12 months prior.

5.0 Pre-Launch Preparation and Early Launch Activities

The pre-launch and launch/early orbit phase of a satellite's lifetime is the period during which safety-related policy decisions are rendered and associated data interfaces established. Safety-related policy decisions carry forward as precedent and actual operational arrangement to form the O/O's safety posture over the satellite's orbital lifetime.

Many pre-launch activities such as establishing interfaces, data sharing agreements, and a Concept of Operations (CONOPS) require coordination. Other activities pertaining to the launch and early orbit period such as outlining particular practices and reporting are needed to conduct conjunction assessment activities during this phase of orbital life and to facilitate a smooth transition into on-orbit conjunction assessment. Each activity is treated individually in this section.

5.1. CONOPS Discussions and Arrangements with USSPACECOM Pertaining to Launch Phase

A spacecraft's journey from the launch facility to its on-station positioning in its service orbit is complicated and open to mishaps that can damage both the launching spacecraft and other spacecraft in proximity. The U.S. Government performs required activities in support of the launch enterprise including cataloging the spacecraft and any other space objects, debris and otherwise, related to the launch. To meet these responsibilities and provide a safe exercise of the launch process, the spacecraft operator needs to execute several pre-launch activities and points of coordination. This is best done by coordinating with USSPACECOM to discuss all the related issues, exchange information, and generate a comprehensive launch and deployment plan so that all affected agencies can exercise their proper roles.

First, early cataloging is extremely important to enable the conjunction assessment process to protect all other on-orbit assets. To assist the cataloging function, all aspects of the launch delivery and deployment methodology need to be fully documented and communicated to USSPACECOM so that those performing the launch cataloging process know what to expect at each point and can respond appropriately.

Aspects of the launch delivery that may affect cataloging and should be documented would include the launch vehicle configuration (rocket versus air launch) and the launch phases (parking orbits, transfer orbits, injection, and post-injection transiting to on-station locations).

The deployment methodology includes timing post-separation and number of objects deployed. Examples of unusual deployment features that might create cataloging issues include high-velocity deployments, non-immediate deployments (i.e., subsequent deployment of a satellite from one of the deployed satellites), and tethered satellites. 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.

Input for the R-15 launch form (launch plan and orbital parameters) should also be discussed with USSPACECOM so that they may render any necessary clarification or aid. The launch provider is responsible for completing and submitting the R-15 form; however, the O/O should discuss the content with USSPACECOM well in advance of the launch. (See Appendix K for more information.)

Second, detailed launch trajectory information for all launch objects needs to be submitted to USSPACECOM with a Form-22 (on space-track.org) well before the launch date so that a colocation and object avoidance analysis for the launch sequence can be conducted and, if necessary, adjustments made to ensure safety. To avoid close approaches with the ISS and other active spacecraft, it may be necessary to modify the launch sequence slightly and eliminate certain launch times from the launch window. Launch providers frequently take responsibility for these activities, but it is important for O/Os to be aware of the availability and benefits of this service.

Third, to avoid any data transfer failures while the launch is in progress, the required exchange of data between O/O and USSPACECOM during the launch process and the associated formats and timelines need to be established, understood, and exercised prior to launch.

To address this topic, the following specific practices are recommended:

A. Establish contact with USSPACECOM to describe and discuss all aspects of the launch including delivery and deployment methodologies.

B. Space the deployment of multiple spacecraft in a way that enhances the ability of USSPACECOM to quickly identify and differentiate the spacecraft using the SSN.

C. Discuss the preparation of the R-15 launch form with USSPACECOM so that they understand its contents and any implications for safety of flight.

D. Ensure that the launch provider submits the Form 22 and launch trajectory information to USSPACECOM, including ephemerides for the powered flight portions and orbital elements for the parking orbits, so that potential colocation and deconfliction potentialities can be discovered.

E. Provide to USSPACECOM as soon as possible launch-related information (e.g., injection vectors and initial ephemerides for deployed spacecraft) that can be used to assist with the cataloging process, especially to confirm the identity of launch-related objects. Coordinate a satellite numbering scheme (potentially including temporary satellite numbers) appropriate to the launch type and expected degree of cataloging difficulty.

F. Coordinate with USSPACECOM any potential launch anomaly diagnostic products that can be provided if issues arise during the launch and early orbit sequence.

5.2. CONOPS Discussions and Arrangements with USSPACECOM and NASA Pertaining to On-Orbit Mission Phase

USSPACECOM is required to maintain orbit determination solutions on all objects arising from the launch as part of its military space object custody responsibilities. USSPACECOM also provides conjunction assessment information to O/Os for safety of flight. In order for USSPACECOM to maintain the catalog most easily for safety of flight for all, the O/O should provide relevant details about its assets. The pre-launch period is the appropriate time to conduct exchanges of information that facilitate these activities.

1. **Provide operational contact information**. It is important for the satellite operator to provide operational point-of-contact information so that USSPACECOM can coordinate spacecraft tracking, cataloging, identification, and provision of space flight safety data for the satellite. Submitting this information allows expeditious contact if issues arise during the launch and on-orbit periods of the satellite's lifespan and provides the information necessary for USSPACECOM to arrange for the delivery of basic space flight safety services.
2. **Provide information about satellite construction and operation**. Basic information about the satellite to be deployed, such as satellite dimensions, presence of deployable structures (e.g., solar panels, antennae), satellite material properties, and expected satellite regular attitude, needs to be communicated to USSPACECOM. These aspects of satellite construction and operation affect trackability, and an understanding of these construction features allows USSPACECOM to assemble a tracking approach, assign appropriate sensors, and predict the regularity of attempted tracking success.
3. **Provide satellite orbit maintenance strategy**. The orbit maintenance strategy for the satellite should be communicated, at least at a high level. Information such as the logic for determining orbit maintenance maneuvers, the maneuver thruster technology, and the frequency/size/duration of orbit maintenance burns will help USSPACECOM to set up the orbit maintenance parameters properly for each satellite to perform the most reliable orbit maintenance possible.
4. **Provide the satellite flight control and navigation paradigm**. Understanding the flight control and navigation paradigm of the satellite is needed, especially whether a traditional ground-control paradigm has been followed or whether autonomous navigation is used. If the latter, the amount of ground-knowledge of satellite activities, such as whether there is foreknowledge of maneuvers and an opportunity to override these maneuvers from the ground before they are executed, is important to understand the degree to which the satellite's navigation can be manually influenced if necessary. In addition to setting general expectations for the satellite's flight dynamics, this information is helpful in determining the degree of expected fidelity for regularly generated satellite O/O ephemerides.

To address this topic, the following specific practices are recommended:

A. Register the spacecraft with USSPACECOM using the Satellite Registration form on space-track.org.

B. Provide USSPACECOM with basic construction and mission information about the satellite such as stowed dimensions; deployable structures such as solar panels, antennae, booms, including all their (rough) dimensions; satellite material properties and colors; regular satellite attitude; and registered operational radio frequencies.

C. Provide USSPACECOM with a basic overview of the satellite's orbit maintenance strategy including the paradigm for determining when orbit maintenance maneuvers are required; the maneuver technology used (as this relates to burn duration and expected accuracy); and the frequency, duration, and magnitude of typical burns.

D. Provide USSPACECOM with an understanding of the flight control and navigation paradigm, principally whether a ground-based control approach is followed or some degree of (or full) autonomous control is used. If the satellite control does include some autonomous flight dynamics or control features, indicate how much (if any) foreknowledge ground controllers have of autonomous maneuver actions, the amount of information that is communicated to the ground both before and after the maneuver (e.g., maneuver time, delta-V, direction), and whether ground-based overrides are possible.

5.3. CONOPS Discussions and Arrangements with USSPACECOM and NASA Pertaining to Conjunction Assessment

On-orbit conjunction assessment is needed to protect the satellite and keep valuable orbital corridors free of debris pollution and sustainable for the indefinite future. The screening process is the first step in completing a risk analysis for a potential conjunction.

Conjunction assessment screenings typically use O/O ephemerides as a statement of the primary object's position. Ephemeris formats, delivery mechanisms, and screening timetables need to be coordinated with the screening provider. The screening provider should use this information to monitor the satellite's projected position over time and identify potential conjunctions. The O/O needs to choose which screening service provider will be used (i.e., the USSPACECOM free service, a validated commercial conjunction assessment service, or both) and establish a robust interface prior to launch.

USSPACECOM currently provides a free conjunction assessment service that performs conjunction assessment screenings on behalf of an O/O and sends proximity warnings (CDMs) for each situation in which the distance between the O/O's satellite and another cataloged object is smaller than a set threshold. These messages give O/Os the data they need to assess the collision likelihood of a particular conjunction and, if necessary, plan and take mitigative action. As noted in Section 3.1, NASA recommends at a minimum using the USSPACECOM conjunction assessment service, which can be augmented with validated commercial conjunction assessment services when desired. (See the USSPACECOM Spaceflight Safety Handbook for additional information regarding the USSPACECOM conjunction assessment service.)

Commercial providers should provide equivalent support and data formats. Many commercial conjunction assessment services work from the USSPACECOM conjunction assessment data and not from separate or unique commercial SSA data.

Based on satellite orbit and mission characteristics, a screening volume size will need to be assigned. (See the USSPACECOM Spaceflight Safety Handbook for more details.) The screening volume is the physical volume (generally an ellipsoid) that is "flown" along the primary's orbit during the screening process, with any objects found within this volume considered to be conjunctions and associated CDMs generated. If a commercial conjunction assessment provider is selected, the O/O will need to work directly with the provider to discuss the type, timing, and format of the information needed. (See Appendix L for Information about how NASA validates and uses commercial data.)

USSPACECOM distributes CDMs through space-track.org. An O/O needs to register on space-track.org and provide contact information to USSPACECOM to receive the basic level of CDMs. If desired, a test instantiation of space-track.org is available to allow O/Os to practice generating, receiving, and processing the conjunction assessment data products.

Finally, a formal Orbital Data Request (ODR) for any of the desired USSPACECOM-generated conjunction assessment information beyond the most basic products will need to be submitted to USSPACECOM and adjudicated before information exchange can begin. An ODR form is a method to request data and services beyond the basic ones. The form and instructions for filling it out are posted on space-track.org. Non-U.S. Government entities are strongly encouraged to sign SSA sharing agreements with USSPACECOM, which expedites the ODR process. For NASA missions, ODRs are sent to CARA and JSC FOD, who submit them on behalf of the mission. ODRs are used to request permission to redistribute USSPACECOM data to other entities, obtain specialized one-time analyses, and make other specific requests.

Large constellations may require special considerations such as quantity or timeframe of data used for screening and risk analysis. NASA has considerable operational experience with conjunction risk assessment and has assisted previous large constellation operators in designing a conjunction risk assessment process that scales appropriately.

To address this topic, the following specific practices are recommended:

A. Decide whether the USSPACECOM free service, a validated commercial conjunction assessment service, or both will be used by the mission.

B. Establish a service with the selected service provider.

C. Implement a SSA sharing agreement with USSPACECOM to receive advanced data support and services.

D. Through the registration of the satellite with USSPACECOM, begin the process of arranging for conjunction analysis data exchange including O/O ephemerides, maneuver notification reports, and CDMs. USSPACECOM uses the space-track.org account as the mechanism for product exchange.

E. If needed, complete an Orbital Data Request (ODR) form to arrange for delivery of USSPACECOM advanced conjunction analysis products.

F. For large constellations, coordinate with NASA and the screening provider to identify and address any special considerations.

5.4. *In situ* Launch Products and Processes

Once liftoff is achieved, the foci become those of a safe journey to the final on-station destinations of the spacecraft and the efficient performance of the launch cataloging process. To determine whether the launch is nominal and has deposited its spacecraft as expected, the initial injection vector should be provided to USSPACECOM as soon as it is available. Additionally, once initial contact has been made with each spacecraft and initial position information has been downlinked, the generation and forwarding to USSPACECOM of associated predicted ephemerides is very helpful in properly identifying the new spacecraft and, in some cases, finding them in the first place. Finally, to render any desired anomaly support and to assume the appropriate conjunction assessment posture for non-functional spacecraft, it is important to forward (or update on space-track.org) spacecraft status information, especially in the era of “disposable” satellites in which infant mortality is higher.

To address this topic, the following specific practices are recommended:

A. To aid in satellite tracking and identification, provide injection vector(s) to USSPACECOM as soon as they are available.

B. To assist in spacecraft identification for the cataloging process and provide general awareness among all O/Os, generate and forward predicted ephemerides for the spacecraft to USSPACECOM and publish the ephemerides (and all subsequent ephemeris updates) publicly as soon as contact is established with each deployed spacecraft.

C. If USSPACECOM has issued TLEs for launched objects, notify USSPACECOM of the TLE and object number associated with your spacecraft.

D. Provide early reporting to USSPACECOM of any spacecraft failures or other operational difficulties, both to obtain any available anomaly support and to assign the appropriate conjunction assessment approach to the spacecraft (i.e., inactive and thus handled in a manner equivalent to a debris object).

E. If using a commercial provider, make sure it has access to information from items A-D.

6.0 On-Orbit Collision Avoidance

For nearly all spacecraft, the on-orbit phase of their life cycle is the longest, meaning that the conjunction assessment practices and CONOPS in place during this phase will have the greatest impact on the satellite's overall risk exposure.

As explained in Section 3, the conjunction assessment process as presently structured comprises three phases:

1. **Conjunction assessment screenings** identify close approaches between a protected asset, called the primary satellite, and any other space objects, called (from the vantage point of the primary) "secondaries."
2. **Conjunction risk assessment** examines each of the close approaches produced by the screening activity to determine which may represent dangerous situations and therefore require a mitigation action.
3. **Conjunction mitigation** constructs a mitigation action, usually a trajectory change for the primary object, that will both reduce the collision risk of the close approach to an acceptable level and not create any new high-risk conjunction events.

Before any of these three activities can take place, certain satellite data and position information needs to be produced and made available to the conjunction assessment process.

These four aspects of conjunction assessment (required input data and the three phases of the conjunction assessment process) are each treated separately below.

6.1. Spacecraft Information and Orbital Data Needed for Conjunction Assessments

Because conjunction assessment identifies (and if necessary, mitigates) close approaches between spacecraft, it requires access to a comprehensive space catalog of orbital information. The USSPACECOM space catalog is the base catalog used by nearly all conjunction assessment practitioners. Earlier sections of this document described the pre-launch registration and coordination process with USSPACECOM to receive basic launch and on-orbit conjunction assessment services. Several commercial conjunction assessment service providers offer conjunction assessment products derived from alternative space catalogs. O/Os are encouraged to pursue commercial services, particularly when such services offer improvements and innovations above and beyond what is available from USSPACECOM. However, NASA recommends O/Os use the service offered by USSPACECOM as both a baseline and a supplement to commercially procured services. This is because the objects contained in the commercial catalog may not be the same as those in the DOD catalog and because the commercial vendor may provide conjunction assessment services based on publicly available TLEs[8] along with solutions for the objects in their own catalog. These TLE-based solutions are not sufficiently accurate to be used

[8] See Appendix E for more information about the use of TLEs.

for conjunction assessment. (See Appendix L for information about how NASA validates and uses commercial data.)

The USSPACECOM space catalog used for conjunction assessment contains position and uncertainty information for the primary object.

- If the primary object is not maneuverable, it is in principle possible to perform conjunction assessment on its behalf entirely from catalog-based information. However, satellite O/Os generally have a better understanding of the spacecraft’s construction and thus its non-conservative force parameters such as the ballistic coefficient and solar radiation pressure coefficient. So, the O/Os’ prediction of the satellite’s future position, captured in a predictive ephemeris, is often more reliable or at the least an important adjoining datum to the future position information calculated from a space catalog entry.
- For satellites that do maneuver, future position calculations from catalog information alone will not capture any planned trajectory changes and thus will leave undiscovered any satellite conjunctions that could arise from the modified trajectory.

Therefore, for both non-maneuverable and maneuverable spacecraft, but especially for the latter, it is necessary that O/Os furnish predicted satellite state and uncertainty information, usually in the form of an ephemeris that includes state covariance at each ephemeris point. The details of the generation of such ephemerides that result in the most useful product for conjunction assessment are described in the details portion that concludes this section.

While it is most important to submit such ephemerides to the screening entity, it is also helpful to place them on a public-facing website for any space operator to download and process. Mutual sharing of expected future positions is the best way for active satellites to avoid collisions with each other. Claims that predicted ephemerides contain proprietary information of any consequence are simply not compelling and, in any case, are outweighed by the safety benefit of exchanging such information. Such ephemerides should be recomputed and reissued/reposted as soon as a change to a spacecraft’s intended trajectory is planned.

In determining how to react when a primary satellite is found to be in conjunction with a secondary, the logic path is governed heavily by whether the secondary object is an active, maneuverable spacecraft.

- If the object is non-maneuverable, then the object will follow a Keplerian orbit without unexpected perturbations. Future positions can be predicted in a straightforward way using a dynamical model.
- If the object is an active spacecraft that either has shown a history of maneuvering or is believed to be maneuverable, then it is quite possible that trajectory-changing maneuvers are planned and the assumption of a Keplerian orbit is not appropriate.

For this reason, it is important to know whether any given spacecraft is active, capable of maneuvering, and presently in a phase of satellite life in which maneuvering is possible. This status can be documented and communicated by the O/Os’ setting of the spacecraft’s active/dead and maneuverable/non-maneuverable flags in its space-track.org record. This allows other O/Os to determine whether the satellite can or will change its trajectory in a non-Keplerian manner and thus consider this possibility in conjunction assessment.

O/Os of active, maneuverable spacecraft should provide USSPACECOM with information outlining basic information about each planned maneuver. This data should be uploaded to www.space-track.org for the most efficient use. While in principle such information could be reconstructed from submitted ephemerides, it is simpler and more accurate to provide the information directly in this form. Providing maneuver notifications assists USSPACECOM in updating their own catalog as they know when to look for maneuver activity and, if discovered (and subsequently tracked), can expeditiously update the satellite's catalog entry to reflect the new trajectory. Of course, forwarding maneuver notifications is not a substitute for sending updated ephemerides that contain the intended maneuvers. Rather, it is an accompanying notification that allows better use of the received ephemerides and facilitates the USSPACECOM mission.

More O/Os are considering or are including autonomous flight control features, especially in large constellations in which the constellation management functions are complex. Autonomous flight control features may include orbit maintenance maneuvers and, in some cases, even conjunction risk mitigation maneuvers that are developed, scheduled, and executed from the onboard control system without any active ground-based participation. While such approaches can offer improved efficiencies, they present their own challenges.

Even if satellite maneuvers are planned and executed autonomously, these planned maneuvers must be included in ephemerides and made available in near real time both to the screening provider and more broadly. This is because, recognizing the latencies of the download and distribution mechanisms, satellite maneuvers must not be executed without sufficient advance notice to allow the conjunction assessment process to become aware of the intended maneuver and ensure its safety. The amount of advance notice required is governed by the latencies in the selected conjunction assessment process, which includes the O/O infrastructure to receive and react to conjunction assessment information from the screening provider. The principal difficulty is notifying other active, maneuverable satellites that may be contemplating their own maneuvers. Maneuver intentions must be shared with other such O/Os in a satellite's vicinity to ensure that intended maneuvers by either or both operators, if executed, do not place both satellites on a collision course.

To address this topic, the following specific practices are recommended:

A. Actively maintain the space-track.org record for the satellite, updating the active/dead and maneuverable/non-maneuverable flags to reflect the satellite's current status.

B. Furnish predicted ephemerides that include state covariances to USSPACECOM (and any additional commercial screening provider) and set the privileges to allow any interested party to access and download this information.

C. Furnished ephemerides should possess the following characteristics:
    a. Be of a 7-day predictive duration for LEO and 14 days for other orbits;
    b. Be issued at least at the following frequencies:
        i. Three times daily for spacecraft with perigee heights less than 500 km;
        ii. Daily for other LEO orbits; and
        iii. Twice weekly for other orbits.
    c. Include all known maneuvers within the ephemerides' prediction duration.
    d. Provide ephemeris point spacing of approximately 1/100th of an orbit, in either time or true anomaly. (Certain scientific missions with extremely long orbits or high eccentricities may require more specialized approaches.)
    e. Contain a realistic covariance at each ephemeris point for at least the six estimated state parameters. (Appendix I provides a practical guide for assessing covariance realism, as well as some general principles for tuning the covariance production process.)
    f. Be formatted and distributed in the Consultative Committee for Space Data Systems (CCSDS) standard Orbital Ephemeris Message (OEM) format, preferably in the J2000 reference frame.

D. Furnish maneuver reports to USSPACECOM for any trajectory-altering satellite maneuvers sufficiently in advance of maneuver execution to enable an O/O evaluation of the maneuver's safety. Employ the standard maneuver reporting message for this notification.

E. When a maneuver becomes part of a satellite's trajectory plan, generate and submit to the screening provider an updated ephemeris that contains this new maneuver as early as is feasible but certainly with sufficient advance notice to enable an O/O evaluation of the maneuver's safety.

6.2. Conjunction Assessment Screenings

The first step in the conjunction assessment process is to find close approaches between protected (primary) objects and other objects, with the latter object set's positions represented either by ephemerides (if they are active spacecraft) or space catalog entries. Finding these close approaches is accomplished by conjunction assessment screenings in which the predicted positions of the primary object and all other space objects that survive a pre-filtering process are compared.

At USSPACECOM, conjunction assessment screenings are executed using a volumetric-based approach: a physical screening volume (usually an ellipsoid) is “flown” along the primary object’s trajectory, and any secondary trajectories that penetrate this volume are considered conjuncting objects. This screening is accomplished using a tool called the Astrodynamics Support Workstation (ASW).

Volumetric screenings generate more close approaches than probabilistic or “covariance-based” methods but are preferable because they essentially give a snapshot of the satellite catalog in the vicinity of the primary’s ephemeris. If the screening volume is large enough, the conjunction information can be used to determine the safety of not just the nominal trajectory but also any reasonably sized maneuvers that the primary may choose to make.

Once these close approach objects are identified, further processing is invoked to determine the precise time of closest approach between the two objects and the two objects’ states and covariances at that time.

A protected asset should be screened for close approaches against a comprehensive satellite catalog at least daily with the results of this process obtained and processed by the O/O, also at least daily. For active, maneuverable satellites that submit ephemerides to the screening process as a way of including their planned maneuvers into their predicted trajectories, these ephemerides should be screened against each other (subject to appropriate pre-filtering) in near real time whenever an O/O submits an updated ephemeris. These “O/O vs O/O” screenings are the best way to ensure that maneuver plans are communicated among O/Os to prevent simultaneous maneuvers from causing a collision.

Current USSPACECOM practice is to conduct three screenings per day. Each screening predicts close approaches between:

1. The ASW solution for each protected (active) asset against the full catalog;
2. O/O ephemerides submitted after the last screening against the full catalog; and
3. O/O ephemerides submitted after the last screening against all other unexpired O/O-submitted ephemerides.

In other words, O/O-submitted ephemerides are screened against the full catalog when initially submitted, then retained and screened against other O/O ephemerides until they expire.

Three screenings per day is a minimum frequency for higher-drag orbit regimes such as LEO orbits with perigee heights below 500 km; daily screenings for other orbit regimes yields sufficient accuracy.

(See the USSPACECOM Spaceflight Safety Handbook for details about the cadence and conduct of conjunction assessment screenings.)

To address this topic, the following specific practices are recommended:

A. Submit predicted ephemerides for the spacecraft to a screening provider to be screened for conjunctions at least daily with spacecraft in higher-drag orbit regimes screened at least three times per day.

B. Ensure that an O/O ephemeris for an active, maneuverable spacecraft is screened against other ephemerides from active, maneuverable spacecraft in near real time after any such ephemeris is submitted to the screening provider.

C. Obtain and process these screening results from the screening provider at the same frequency at which they are produced for both the full-catalog and O/O vs O/O screening cases described above.

6.3. Conjunction Risk Assessment

Satellite conjunctions are approaches between two satellites closer than a specified set of distances, which is often chosen to be much larger than the set that would pose an actual collision threat. A key next step, therefore, is to evaluate each conjunction to determine if it poses, or is likely to pose, a substantial risk of collision. This evaluation activity, called conjunction risk assessment, comprises both the key calculations that feed the concept of risk (that is, both collision likelihood and collision consequence) and the evaluations of the input data that subtend these calculations to ensure that they constitute a basis for decision making. Only conjunctions that are determined to be high risk merit the consideration of mitigation actions.

Methods proposed in the scientific literature for calculating and assessing satellite collision likelihood have different merits and different risk tolerance orientations. Of all the possibilities, Pc is the oldest, most straightforward, and most widely embraced collision likelihood parameter. Because it is a present industry standard, NASA recommends that operators employ Pc as the foundational element of their collision likelihood assessment. (See Appendix M for an extended treatment of the recommendation for the use of Pc as the collision likelihood parameter.)

Two approaches to calculating the Pc are:

1. The “two-dimensional” Pc (2D-Pc) calculation approach, which was originally introduced by Foster and Estes in 1992 with theoretical clarifications by Alfano (2005b) and Chan (2008). This method is a durable simplification of the calculation that is valid in most instances, but there are situations in which it does not perform accurately.
2. The “three-dimensional” Pc (3D-Pc) calculation method, which was originally formulated by Coppola (2012) and “repaired” and extended by CARA. Once it has completed final NASA validation, it is expected to be the recommended analytic approach. This method is accurate for nearly every situation, tests exist to identify those very few cases in which it may not be fully adequate, and it is computationally efficient.

Additionally, the primary and secondary object covariances for some orbit regimes can contain significant correlated error, thus introducing inaccuracy in the calculated Pc. (See Appendix N for a more detailed discussion of Pc calculation methods and related issues.)

Software (including source code, test cases, and documentation) to calculate the Pc using both the traditional two-dimensional and (when validated) the presently recommended three-dimensional technique and to remove correlated error between the primary and secondary covariances can be obtained free of charge at the public-facing CARA software repository. (See Section 7 in this document for the specific URL.)

The value of the Pc threshold at which an O/O would choose to mitigate a conjunction is a function of both the O/O's risk tolerance and the volume of conjunctions that the O/O is able to mitigate. In the conjunction assessment mission area, however, there has been broad convergence on a per-event Pc mitigation threshold value of 1E-04, meaning that remediation actions are recommended when the likelihood of collision is greater than 1 in 10,000. Missions that wish a more conservative risk posture can select a more demanding Pc threshold such as 1E-05. This infused conservatism may allow more streamlined risk assessment techniques in other areas.

Finally, some practitioners like to include an additional imperative to mitigate when the predicted miss distance is smaller than the hard-body radius or a distance close to the hard-body radius value. This predicted miss distance approach would need to be invoked only rarely because a small miss distance typically produces a Pc that violates most commonly accepted Pc mitigation thresholds. (See Appendix N for more information about the hard-body radius calculation.)

Other risk assessment methods exist (e.g., Alfano 2005b, Carpenter and Markey 2014, Balch et al. 2019) and are generally considered to be more conservative than the Pc-based methodology advocated above. O/Os are encouraged to employ a more conservative conjunction assessment approach if it suits their risk posture. However, the Pc method and the mitigation threshold of 1E-04 enjoy wide acceptance in the conjunction assessment industry and historically have provided a sustainable balance between safety and mission impact.

Risk is the product of the likelihood of an unfavorable event and the consequence of that event, should it occur. For some time, it has been presumed that any satellite collision is a catastrophic event that is to be avoided by any means possible. In most cases, such events will render an active satellite unusable, presenting a very serious risk to the O/O. Therefore, the likelihood (Pc) was computed, and the consequence was not factored into the computation.

However, as the orbit environment grows, there may come a point when an O/O is faced with too many conjunctions to avoid individually. In this case, one method to triage the conjunctions to determine which should be mitigated to best protect both the spacecraft and the orbital environment is computation and application of the consequence as part of the risk determination.

Satellite collisions, depending on satellite masses and relative velocity, can produce wildly different amounts of orbital debris from a handful of pieces to many thousands of pieces large enough to critically damage a spacecraft. To be sure, introducing any debris at all into the space environment is to be avoided. Conjunctions that, if they were to result in a collision, would produce only a small amount of debris (maybe fewer than 50 pieces) could be addressed using a more lenient mitigation threshold to prioritize them appropriately against those that would create more debris. A threshold that is an order of magnitude more lenient than what is used for high-debris conjunctions would align in magnitude with other situations in which relaxing the mitigation threshold is warranted (Hejduk et al. 2017). (See Appendix O for a more expansive treatment of the assessment of a conjunction's debris production potential. See the CARA software repository for software to calculate debris production potential; see Section 7 in this document for the specific URL.)

Finally, the data used to calculate the parameters that feed the risk assessment decision, namely the state estimates and accompanying uncertainty volumes (covariances) for the primary and secondary objects, must be examined to determine whether they manifest problematic elements that would prevent the calculated parameters from serving as a basis for conjunction mitigation actions. In such cases, it is possible that executing a mitigation action based on those data could make the conjunction situation worse rather than better.

A non-actionability situation with USSPACECOM conjunction assessment products occurs occasionally. For example, an object whose state has been propagated longer than the orbit determination fit-span in order to reach TCA is considered under most conditions to be insufficiently tracked and over-propagated and thus not suitable as a basis for conjunction mitigation actions. (See Appendix P for a recommended procedure to evaluate USSPACECOM conjunction assessment products for actionability.) Occasionally one of the two objects in a conjunction lacks a covariance, making probabilistic conjunction assessment impossible but still enabling other risk assessment methods. (See Appendix P for a discussion of such situations.)

To address this topic, the following specific practices are recommended:

A. Use the Probability of Collision (Pc) as the principal collision likelihood assessment metric.

B. Pursue mitigation if the Pc value exceeds 1E-04 (1 in 10,000).

C. Pursue mitigation if the estimated total miss distance is less than the hard-body radius value.

D. Employ the current operational NASA Pc calculation methodology for routine Pc calculation. Consider removing correlated error from the primary and secondary object joint covariance.

E. As a prioritization method for situations in which the number of conjunctions meeting mitigation criteria exceeds the ability of the O/O to mitigate, estimate the amount of debris that a conjunction would produce if it were to result in a collision. A less stringent Pc an order of magnitude lower could be appropriate in such cases.

F. If employing USSPACECOM data products for conjunction assessment, use the procedure given in Appendix P to determine whether the data for a particular conjunction are actionable and thus constitute a basis for conjunction assessment-related decisions.

G. If a different conjunction assessment product provider is chosen, develop and employ data actionability criteria for this provider's conjunction assessment information to determine conjunction assessment event actionability.

6.4. Conjunction Risk Mitigation

O/Os with satellites that possess the ability to mitigate conjunctions have a responsibility to perform mitigation actions when required. In practical terms, this means that a mitigation action should be tendered when a conjunction's risk parameter, usually the Pc, exceeds the mitigation threshold at the "maneuver commitment point," which is that point in time before the TCA when a decision to mitigate is needed in order for the mitigation action to be in place before the TCA actually occurs. The most typical (and effective) mitigation action is changing the satellite's trajectory to avoid a possible collision with the secondary either by thrusting to effect a satellite maneuver or, in some cases, changing the satellite's attitude to alter its drag coefficient and thus its trajectory. An additional, although generally much less effective approach is to change the satellite's attitude simply to reduce the satellite's cross-sectional area in the direction of the oncoming secondary. This does not fully mitigate the close approach but reduces the likelihood of an actual collision between the two objects.

When planning a mitigation action, the general practice is to choose a trajectory alteration that reduces the Pc for the conjunction by 1 to 2 orders of magnitude. A recent study (Hall 2019a) showed that a Pc reduction by 1.5 orders of magnitude (that is, by a factor of ~0.03) marked the beginning of diminishing return with regard to lifetime satellite collision risk. Therefore, NASA recommends a minimum of 1.5 orders of magnitude reduction in Pc as a post-mitigation Pc goal;

i.e., if the recommended mitigation threshold of 1E-04 is used, the post-mitigation goal would be ~3.2E-06 or lower.

In general, there is a trade-off between mitigation maneuver size and maneuver execution time. To mitigate a conjunction adequately, smaller maneuvers can be used if the maneuver is made earlier; that is, farther in advance of TCA. Waiting until closer to TCA will typically require a larger maneuver to achieve the same Pc reduction. However, because most conjunction events drop off to a low level of risk before TCA (due to additional tracking and improved state estimates and covariances), waiting until closer to TCA to perform a mitigation action increases the likelihood that it can be determined not to be necessary. Thus, O/Os must decide in each case whether they wish to act earlier with a less invasive action required or whether they wish to wait until closer to TCA in the hopes of observing the collision likelihood drop below the mitigation threshold and thus being able to waive off the maneuver, but knowing that, if an action is still required, it will be larger and more disruptive. There is no clear rubric for how to proceed in such cases, but external considerations, such as staffing availability for a later maneuver and amount of disruption that a large maneuver would require, often govern the decision.

When performing a trajectory-changing mitigation action, “new” conjunctions and/or elevated Pc values of existing conjunctions often occur. O/Os should ensure any mitigation action does not render the overall safety-of-flight evaluation worse by producing a more dangerous situation than would have existed without the mitigation action. One could examine the amalgamated risk of all the conjunctions in the near future and conduct mitigation planning on this basis, but it is generally acceptable to pursue mitigation of the one conjunction that violates the threshold (and remediate it to a Pc 1.5 orders of magnitude below the threshold) while ensuring that no new conjunctions are produced that exceed the threshold. Using the thresholds recommended here, this means bringing the violating conjunction down to a Pc of 3.2E-06 without introducing or raising any other conjunction Pc values above 1E-04. The best way to ensure that these standards are met is to generate an ephemeris that includes the mitigation action and submit it to the screening provider for a special screening action. This will produce a fresh set of CDMs against the planned mitigation action and allow easy and reliable verification that the Pc values for both the principal conjunction and any ancillary conjunctions remain below the desired levels.

Using larger screening volumes and analyzing the maneuver against the resulting CDMs is another method of determining whether the maneuver creates close approaches. This method creates CDMs for conjunctions that are somewhat far away from the nominal trajectory but might constitute worrisome conjunctions after a maneuver. This method for ensuring the safety of the post-maneuver trajectory is serviceable for debris objects, which will not alter their orbits beyond Keplerian models. However, this method does not protect against potential, yet-to-be-disclosed trajectory changes by other maneuverable satellites.

Choosing a mitigation action for a conjunction against a non-maneuverable secondary is generally straightforward, but the situation is much more complicated when the secondary object is an active, maneuverable spacecraft. While submitted ephemerides from that secondary’s O/O is a statement of that spacecraft’s intended trajectory at the time of production, it is likely that the secondary’s O/O has also noticed the conjunction and may be planning a mitigation action of its own. In addition to the fact that two mitigation actions for the same close approach are unnecessary, there is a real danger that the two mitigation actions could place the two satellites on even more of a collision course than taking no action at all.

Establishing contact with the O/O of an active secondary is critical to jointly establishing a way forward for the particular conjunction. The O/Os should jointly decide which satellite will pursue mitigation (should it remain necessary at the maneuver commitment point) and what the mitigation action will be and constrain the trajectory of the non-mitigating satellite to that given in its published ephemeris until after the TCA has passed.

Given the recent industry trend to extremely large satellite constellations, the individual reaching out to other O/Os is unlikely to scale adequately as such constellations continue to grow. A more automated mechanism for exchanging maneuver intentions among O/Os will likely be necessary. SPD-3 directs the movement of conjunction assessment activities away from DOD to a Federal civil agency by 2024, so it makes sense for this new entity to develop an architecture and protocol for the exchange of this type of information. For the present, O/Os need to share their maneuver intentions with other O/Os through direct contact or a third-party organization, such as the Space Data Association[9] with some amount of manual interaction required.

[9] An international organization that brings together satellite operators to support the controlled, reliable, and efficient sharing of data critical to the safety and integrity of the space environment. The Space Data Association membership includes the world’s major satellite communications companies.

To address this topic, the following specific practices are recommended:

A. When a conjunction's Pc at the mitigation action commitment point exceeds the mitigation threshold (recommended to be 1E-04), pursue a mitigation action that will reduce the Pc by at least 1.5 orders of magnitude from the remediation threshold.

B. Ensure that an ephemeris containing the mitigation action is screened against the full catalog, not a large screening volume collection of CDMs.

C. Ensure that the mitigation action does not create any additional conjunctions with a Pc value above the mitigation threshold (for which the recommended value is 1E-04).

D. When the secondary object is an active, maneuverable spacecraft, reach out to the secondary's O/O and jointly establish a way forward for the particular conjunction, including deciding which spacecraft will maneuver and freezing the other spacecraft's planned trajectory until the TCA has passed.

E. Use space-track.org contact information to engage other O/Os.

6.5. Automated Trajectory Guidance and Maneuvering

Satellite designers are increasingly taking advantage of the automation of maneuver planning and execution to simplify mission operations. Particularly with large constellations of satellites, automation can substantially increase efficiency over traditional flight control techniques. However, the automation processes in which flight dynamics computations and decision making occur largely or even entirely without human intervention, and especially when they are executed on board the satellites themselves, can present real concerns related to space traffic management and the prevention of collisions between satellites.

With traditional ground-computed and executed trajectory adjustments that have humans in the loop, satellite operators can compute maneuvers, produce predicted ephemeris data to transmit to the rest of the community to be screened for conjunctions, and command the execution of safe maneuvers to effect that advertised trajectory. Admittedly, such a technique does not scale easily for large constellations, but it has proven reliable and serviceable for securing safety of flight over years of experience.

However, highly automated systems can now be designed in which satellites, using onboard navigation and a programmed target, can compute their own maneuvers and execute them without notification to, or pre-coordination with, their ground control; in such a case, explicit screening of the maneuver by USSPACECOM or some other screening authority, as well as notification to the rest of the space community, would frequently not be possible. If other space operators are not aware that a satellite is planning a maneuver, the other operators may also plan a maneuver and the two maneuvers taken together may cause a collision.

Operators of automated satellite systems should ensure that, when contemplating a maneuver, the intended time, direction, and magnitude of that maneuver (as well as other event-related data for conjunction risk maneuvers) be communicated to the screening authority at a sufficient interval of time before the maneuver so that the maneuver ephemeris can be screened before execution. This communication is most important in ensuring safety of flight between active maneuverable spacecraft, each of which may be generating maneuver plans that, if executed as intended, will create a collision. Maneuver plans should be shared with the screening authority as a predicted ephemeris and, if possible, a maneuver notification report; and it is highly desirable that this information be shared without restriction, perhaps by posting predicted ephemerides so that any interested party can download them, without restriction.

One method that some operators use to facilitate maneuver planning is to request from the screening authority the use of a screening volume size that encompasses a large amount of orbital space, ensuring that they receive a large set of CDMs that is representative of all the spacecraft operating nearby. The operators then use these CDMs to internally plan maneuvers and screen them against this set of CDMs to ensure that the planned maneuver does not cause a close approach with any of the objects for which they have CDM data. While largely effective against non-maneuvering objects, this practice cannot fully account for the fact that the other objects may themselves be maneuverable spacecraft also altering their trajectories. So, if both maneuverable spacecraft do not send their predicted trajectories back to the screening authority for reconciliation, they will not be aware of each other's plan and may in fact cause a collision.

At some point in the future, an automated clearinghouse may be in place for such information to allow near real time receipt and circulation of ephemerides containing maneuver plans to other O/Os. There is work underway at NASA in partnership with industry to design and prototype a ground node that includes near-real-time screening of submitted ephemerides, as well as mechanisms for the two spacecraft to assign responsibility for mitigating a specific conjunction. Hopefully, this capability will be available as part of the Office of Space Commerce's future space traffic coordination system. Quick and efficient screening of planned maneuvers generated by onboard systems requires the creation and operation of this central, low-latency ephemeris "clearinghouse." So, to achieve this future vision of safe operations, both industrial and governmental action is necessary.

At present, however, the USSPACECOM screening process is performed only once every 8 hours. It is possible that a file received from an operator may just miss a screening opportunity, and therefore it may take up to16 hours to screen the predicted trajectory. Therefore, spacecraft using this information to plan onboard maneuvers are obligated to allow this much time in advance for screening their maneuver prior to executing to ensure safety of other on-orbit neighbors. This timeline also affects non-autonomous spacecraft, as they want to ensure that their planned trajectory is taken into account by the autonomous spacecraft, so they also must include the 16 hour advance notice, although that timeline is more typical for traditional ground-based flight dynamics processes.

Once a maneuver is autonomously planned and submitted for screening, the maneuver should be executed as designed unless an alteration is required for safety of flight. Remaining with the communicated plan, even if more efficient possibilities arise in the interval leading up to maneuver execution, enables the rest of the space community to use the submitted ephemeris as the basis for their own trajectory planning.

There may be situations in which a satellite should not execute an intended maneuver that the automation computes, such as in the presence of a surprise post-maneuver conjunction or a conjunction with an active satellite involving cooperative, human-in-the-loop conjunction event management. It is thus imperative for safety reasons that automated systems include the ability to pause or abort any maneuver planned for execution in response to ground command.

To address this topic, the following specific practices are recommended for use by operators of constellations with automated flight dynamics systems:

A. When an onboard flight dynamics system computes any maneuver to alter the satellite’s orbit for mission or conjunction mitigation purposes, communicate maneuver details to the operating ground control early enough to enable a USSPACECOM screening and appropriate action in response to the screening results.

B. Share maneuver plans with USSPACECOM both as a predicted ephemeris with realistic covariance and, when possible, as a maneuver report. Allow these notifications to be publicly viewed and downloaded by any interested party.

C. Execute a maneuver as intended once a maneuver is autonomously planned and externally communicated unless an alteration is required for safety of flight.

D. Include the ability to pause or abort, for safety reasons, any maneuver planned by the automated system, regardless of whether the maneuver is planned by a ground system or on board the satellite.

E. Ensure an automated maneuvering system can temporarily suspend automatic conjunction assessment activities to allow another operator to maneuver.

F. Rapidly submit a new ephemeris for screening if a maneuver is not executed as planned in the original file sent for screening, such as if a maneuver fails.

G. Keep spacecraft maneuverability status on space-track.org up-to-date so other O/Os know whether any particular satellite is capable of maneuvering.

H. If onboard flight dynamics planning is used, be able to communicate back to operational secondary satellite O/Os that the relevant information to enable a maneuver to mitigate a conjunction between them is on board the satellite and will be acted upon.

I. Request a larger-than-average screening volume from your screening provider to ensure that the “snapshot” of the space catalog available to your satellites is broadly inclusive and thus allows maneuver planning to take cognizance of all possible hazards in choosing a new trajectory. This maximizes the chances that, when screened before execution, the chosen maneuver will be safe.

6.6. Other Considerations

The items in this section are best practices that affect orbit design and so, while not directly related to the conjunction assessment process, are appropriate to consider.

Light Pollution. After the launch of the initial portion of the SpaceX Starlink constellation, astronomers noticed that their observing campaigns were being affected by extremely bright, detector-saturating streaks due to the Starlink vehicles. To minimize interference with Earth-based astronomy, O/Os should ensure that spacecraft are built and flown in such a way as to minimize the creation of light pollution.

Adverse astronomical effects arise from satellites reflecting sunlight (e.g., in the visible and near-infrared (IR) spectral bands) and emitting radiation (e.g., in the thermal-IR and radio bands), as well as from occultations in which satellites block the light from astronomical objects. Ground-based sensors in the visible and near-IR bands are most challenged by constellations with satellites that are brighter than about 7th stellar magnitude and that glint brightly in reflected sunlight, especially if deployed at inclinations close to the observatory latitude, and, counterintuitively, at higher orbital altitudes (Walker et al. 2020; Bassa et al. 2022). Comparable orbit inclinations and observatory latitudes result in significantly more frequent crossings of the telescope's field of view. Higher altitudes result in a lower relative velocity between satellite and telescope, which increases dwell-time on each sensor pixel, causing saturation that irreparably contaminates data. Lower altitude satellites also tend to enter Earth's shadow earlier during astronomical nighttime periods, decreasing the duration of their adverse effects, even though they still can cause light pollution during twilight periods.

To preserve the appearance of the night sky and limit adverse effects on ground-based observations, the consensus recommendation of the astronomical community is to keep satellites fainter than the recommended V-band magnitude limit of $M_V = 7 + 2.5\log_{10}(h/550\text{km})$, with h indicating the altitude (Walker et al. 2020). This corresponds to $M_V = 7$ for the population of Starlink constellation satellites currently deployed at 550 km altitude, and $M_V = 7.85$ for the OneWeb satellites at 1,200 km. Factors that affect the brightness of individual satellites include size, albedo, surface characteristics, degree of specular vs diffuse reflection, self-shadowing, and orientation, as well as observation and illumination ranges and angles. Both a constellation's overall population and individual satellite brightnesses are important considerations because ground-based observations will be affected significantly by the existence of large numbers of bright satellites during astronomical nighttime observing conditions. Hall (2022) describes a method of evaluating light pollution levels for proposed or nascent constellations that incorporates a constellation's population, orbital distribution, and empirical or modeled brightness distribution to estimate the number of brighter-than-recommended satellites statistically expected to exist above observatories distributed over the Earth and throughout a year. Notably, using this method, if all of a constellation's satellites are consistently fainter than the recommended M_V limit given above, then even a large constellation could be evaluated to have acceptable visible and near-IR band light pollution levels. (This evaluation method is included in the *EvaluateConstellation* function of the Software Development Kit (SDK) in the NASA CARA software repository. See Section 7, Contact Information in this document for the specific URL.)

For constellations duplicating the same (or similar) manufacturing design for a large satellite population, O/Os should not rely on rough analyses or first-order assumptions about expected brightnesses. Instead, a full satellite brightness model that includes Bidirectional Reflectance

Distribution Function (BRDF) characterization of surface materials should be undertaken during the design phase to estimate the brightness distributions of the deployed constellation. O/Os should consider all mission phases including launch, ascent, and descent (Seitzer 2020). The SATCON-1 Workshop[10] Report (Walker et al. 2020) provides the following four specific recommendations for constellation O/Os to encourage careful up-front design to minimize brightness and avoid glints to the greatest extent possible:

- LEO constellation operators should perform adequate laboratory BRDF measurements as part of their satellite design and development phase. This would be particularly effective when paired with a reflectance simulation analysis.
- Reflected sunlight ideally should vary slowly with orbital phase as recorded by high etendue (effective area × field of view), large-aperture ground-based telescopes to be fainter than $7 + 2.5\log_{10}(h/550\text{km})$, equivalent to 44 × (550km/h) W/steradian.
- Operators should make their best effort to avoid specular reflection (flares) in the direction of observatories. If such flares do occur, accurate timing information from ground-based observing will be required for avoidance.
- Pointing avoidance by observatories is achieved most readily if the immediate post-launch satellite configuration is clumped as tightly as possible consistent with safety, affording rapid passage of the train through a given pointing area. In addition, satellite attitudes should be adjusted to minimize reflected light on the ground track.

If possible, brightness distributions should also be measured using ground-based photometric observations of actual satellites (if already orbiting for partially deployed constellations) or scaled from observations of orbiting prototype/analog satellites based on a similar manufacturing design (if available). Hall (2022) describes how such empirical, ground-based brightness distributions can be used to estimate astronomical light pollution levels, even for constellations deployed in multiple altitude shells and with different inclinations. The SATCON-2 Workshop Report (Walker et al. 2021) describes the on-going effort to establish the "Sathub" repository of photometric observations of constellation satellites, as well as several software tools to aid both astronomers and constellation O/Os in the effort to mitigate astronomical light pollution.

[10] The National Science Foundation's (NSF's) National Optical-Infrared Astronomy Research Laboratory (NOIRLab) and the American Astronomical Society, with support from NSF, hosted the Satellite Constellations 1 (SATCON1) workshop virtually from 29 June to 2 July 2020.

To address this topic, the following specific practices are recommended:

A. As part of spacecraft physical design and orbit selection, perform a spacecraft photometric brightness analysis to determine whether the spacecraft is likely to present an impediment to ground-based astronomy. Consider changes to the satellite’s construction, materials, or operating attitudes to reduce expected photometric brightness to levels that will not impede ground-based astronomy.

B. If a large constellation is being planned, either use a full BRDF-based photometric model or ground-based observations of actual orbiting satellites, if available, to obtain a durable estimate of the entire constellation’s expected brightness distribution as deployed on orbit.

C. If the constellation, given its population, orbit, and constituent satellites, is likely to affect ground-based astronomy, reassign the satellite orbits or modify the satellite construction to eliminate this effect.

7.0 Contact Information

Below is the contact information for the resources mentioned in this handbook.

Table 7-1 NASA Contact and Reference Information

NASA JSC FOD	Human Space Flight Conjunction Assessment Operations jsc-dl-topo-iwg@mail.nasa.gov
NASA CARA	NASA CARA Operations cara-management@lists.nasa.gov
NASA CARA Software Repository	https://github.com/nasa/CARA_Analysis_Tools

For NASA personnel, CARA or JSC FOD serves as the single point of contact between NASA and DOD (e.g., 18 SDS and USSPACECOM) for SSA data and support required for conjunction assessment and risk analysis of NASA missions. The roles of CARA and JSC FOD are defined in NPR 8079.1.

For non-NASA personnel, Table 7-2 provides useful points of contacts.

Table 7-2 Contact and Reference Information for Non-NASA Personnel

Organization	Contact Information and URLs of Interest
USSPACECOM / 18 SDS	Diana McKissock; Cynthia Wilson 18SPCS.DOO.CustomerService@us.af.mil +1-805-606-2675 *Spaceflight Safety Handbook for Satellite Operators* https://www.space-track.org/documents/Spaceflight_Safety_Handbook_for_Operators.pdf *Launch Conjunction Assessment Handbook* https://www.space-track.org/documents/LCA_Handbook.pdf *Space-Track Handbook for Operators* https://www.space-track.org/documents/Spacetrack_Handbook_for_Operators.pdf

Organization	Contact Information and URLs of Interest
	Description of Space Situational Awareness Sharing basic and advanced services, forms, and data examples: https://www.space-track.org/documentation#/odr
USSPACECOM	USSPACECOM.SSA.Agreement-Requests@us.af.mil
NASA Examples	NASA Examples of Information to Expedite Review of Commercial Operator Applications to Regulatory Agencies: https://www.nasa.gov/recommendations-commercial-space-operators

To provide feedback on this handbook, email: ca-handbook-feedback@nasa.onmicrosoft.com