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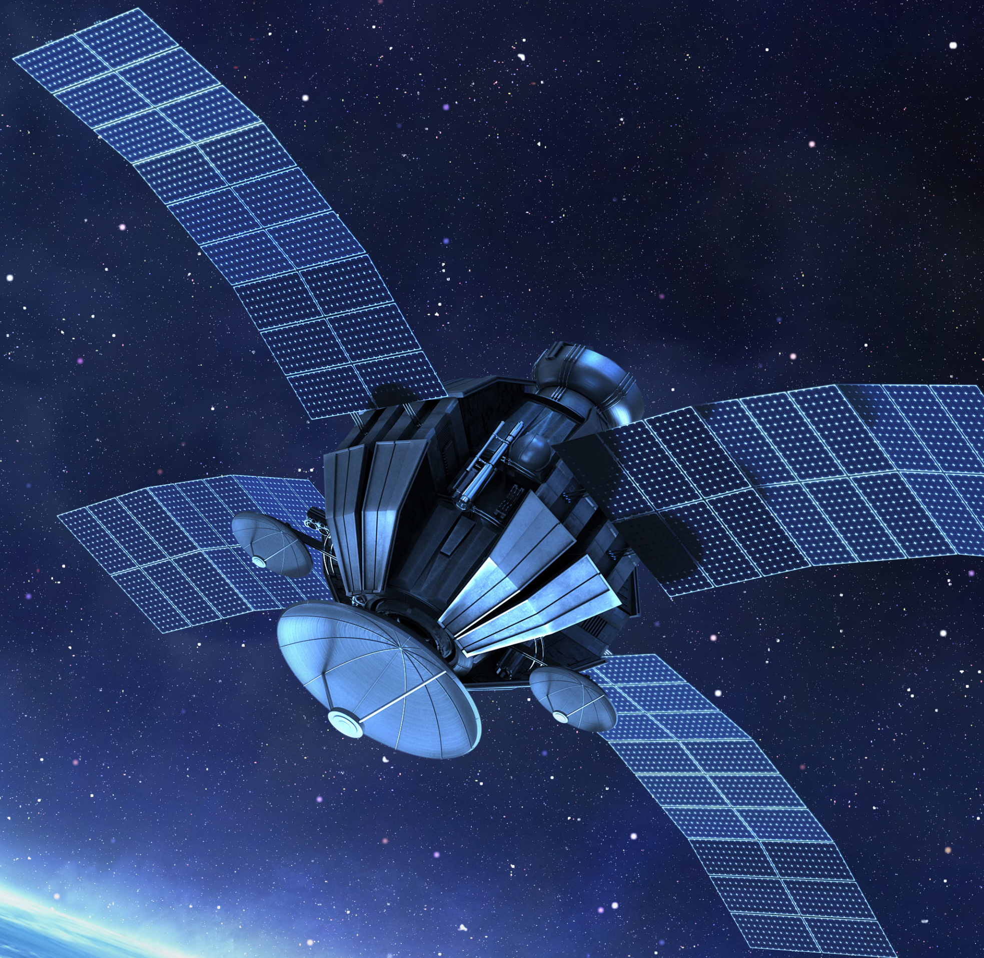

Orbital Safety Best Practices for Satellite Operators

A best practices reference document to guide and improve cooperative operations in space, helping to ensure that future generations maximize the benefits of space.

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VERSION 3.0

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Introduction

For the last 15 years, the pace of activities in space has significantly increased, providing new capabilities that contribute to economic growth, improve science, and better connect the global community. To bring and extend the benefits of these services, satellite operators from around the world have developed increasingly sophisticated constellations leveraging satellites equipped with advanced technology. In 2022, major operators came together and produced a comprehensive set of best practices focused on safety, drawn from years of operational experience and the understanding that comes from working together to maintain sustainable space activities. The authors of this document recognize that space sustainability has other dimensions, such as the concern for dark and quiet skies, but the focus of this effort remains on operational safety in space. The updated version (2026) includes additional operators and lessons learned from further experience resulting in a refinement of the original recommendations and the inclusion of new recommendations to reflect the evolving operational environment. This set of best practices can guide and improve cooperative operations in space, helping to ensure that future generations maximize the benefits of space. The authors recognize that some of the cited best practices are aspirational, as the global infrastructure and procedures to execute some of the recommendations, such as data sharing and active debris removal, are still under development.

In recent years, the private sector has joined an increasing number of countries launching satellites accelerating the growth of the global space economy. The maturation of small and smaller satellites provides a means to less expensively and more rapidly replace and upgrade older technology, which has led to the deployment of satellite constellations to provide services ranging from remote sensing to high-speed broadband internet access. Given the rapid innovation occurring in the space sector, governments have a responsibility to put appropriate regulatory structures in place that keep pace with and promote this innovation. **To be effective, these regulations must strike the appropriate balance of maintaining sustainable operations in space without stifling innovation or preventing new applications that bring tangible benefits to the public and governments.** Striking this balance is not straightforward, especially considering that space is a global domain, meaning individual countries must avoid creating an unmanageable patchwork of conflicting and incongruous rules.

Innovation happens continuously and technological development of satellite systems cannot wait for what promises to be a long and arduous road to appropriate rules that govern space and operations. Guidelines and best practices that establish goals for the design and operation for new and emerging systems are generally more effective than unbending and static regulations. In addition, because of the fast rate of change in technology, regulations quickly become out of date and can serve to lock in aging technology at the expense of modernization and upgrades. Evolving best practices can provide the flexibility necessary to upgrade older technology and facilitate further innovation that improves both space operations and life on the ground. The private sector has unified incentives to work together to safeguard the orbits where it does business. As technology improves, appropriate regulations can be developed that do not create barriers to innovation in areas where it is most likely to occur based on experience gained as the industry matures.

Regardless of the status of regulations, the private sector recognizes that self-interest demands an environment that provides for the safe and efficient operation of satellite networks. The satellite industry, understanding the need to have a well-understood set of operational principles, safety standards, and behaviors that allow all operators to thrive, has worked together in several venues, both domestic and international, to discuss and document best practices or safety standards. Consequently, some "how-to" documents exist that explain the space domain and how to operate spacecraft safely and minimize debris generation in space, providing valuable advice to the many new entrants. For example:

» The "NASA Spacecraft Conjunction Assessment and Collision Avoidance (CARA) Best Practices Handbook" provides detailed step-by-step instructions on how to work with the 18th Space Defense Squadron (Conjunction Assessment responsibilities have now been transferred to the 19th Space Defense Squadron), which currently provides collision warnings and information on how conjunction analysis is performed.

- The Secure World Foundation's "Handbook for New Actors in Space" is a primer for those new to the space sector and provides terminology, an overview of the sector, and suggestions for how to successfully engage.
- Individual operators have posted public-facing and detailed explanations of how their systems approach space safety and issues, like satellite brightness, that are important to the astronomy community.

Other work has focused on space safety and sustainability.

- The U.S. Space Force's "Spaceflight Safety Handbook for Satellite Operators" provides background information and comprehensive details about their services and how to interact productively with them for conjunction services.
- The Space Safety Coalition's "Best Practices for the Sustainability of Space Operations" focuses on specific measures and guidelines for operators to consider that enhance the safety and sustainability of the space domain.
- "Inter-Agency Space Debris Coordination Committee (IADC) Space Debris Guidelines" provide information on debris mitigation guidelines with an emphasis on cost-effectiveness. The IADC is an international forum of space agencies, authorized governmental or inter-governmental entities.
- "United Nations Committee on the Peaceful Use of Outer Space (UNCOPUOS) Long Term Sustainability Guidelines" outline areas of concern and propose measures for ensuring the long-term sustainability of space as a domain for all.

Operators should familiarize themselves with these documents. While additional materials have been developed on the topic of orbital safety, debris management, and space situational traffic coordination, the above cited documents, together, provide a sufficiently comprehensive body of work to underpin this effort. To be clear, best practices articulated in this document do not contradict or supersede earlier works. Instead, they are intended to provide a more strategic, comprehensive, and broadly applicable set of guiding principles and best practices as compared to the more detailed, tactical, and nuanced recommendations in the handbooks referenced above.

Specifically, the best practices presented in this document are designed to be applicable to any operator anywhere in the world, regardless of how they receive conjunction warnings, and represent the best practices that the signatories have already adopted or plan on adopting. Ideally, the best practices contained herein can provide a foundation for discussions leading to a global consensus of behaviors.

A

Design Time

PRACTICE A-1

Consider collision avoidance (CA) implications when choosing insertion and operational orbits

Orbital regimes, and specific orbits within those regimes, have very different object populations and imputed CA burdens and workloads. It is thus important to consider the potential CA implications of any particular orbit choice, as relatively minor changes to a selected orbit can significantly alter the satellite's CA landscape. The following specific considerations should be fully explored and adjudicated by your engineers at design time:

» Perform an analysis to determine whether your spacecraft, once in its operational orbit, will be collocated with other active payloads with a maintained orbit and thus present systematic conjunctions. Consider making minor changes to the orbit to eliminate any systematic conjunctions; if this is not possible, coordinate with the other owner/operators (O/O), and well before launch, establish CA communication and adjudication protocols for resolving the expected regularly occurring conjunctions

- *Rationale: Systematic conjunctions are situations in which two objects will regularly and repeatedly come into conjunction and present collision risks. Systematic conjunctions between two active payloads are particularly problematic for CA because of the necessary coordination between the two O/Os for making potential mitigation decisions.*

» Characterize the conjunction risk for launch and early orbit operations at the insertion altitude. Coordinate with other O/Os, and well before launch, establish CA communication and adjudication protocols for resolving any potential conjunctions.

- *Rationale: Anticipating and mitigating potential conjunctions that occur during the insertion phase in the design phase, before launch, reduces risk for all operators and facilitates space sustainability.*

» Share a sample of your intended guidance targets with control limits that are sufficient to define your orbital shells.

- *Rationale: For safety by design, long-term repeating interactions* *between satellites and constellations should be avoided. Managed conjunctions should be limited to shorter term transitions such as orbit lowering, early operations, or other substantial orbit changes of one or both parties. Guidance targets can help identify and avoid repeating conjunctions by, for example, shell separation of frozen orbits that maintain nearly constant altitude profiles. Guidance targets should use well-defined orbital elements with an epoch and coordinate frame, and the expressed orbits should be reproducible by others.*

» Arrange for a reasonable and prudent separation in altitude with any neighboring constellation if you are planning a constellation of satellites. Such a separation would typically be on the order of at least a few kilometers in altitude if the orbits are frozen.

- *Rationale: Sufficient separation accommodates stationkeeping, collision on launch assessment (COLA), and eccentricity differences.*

» Ensure that your CA concept of operations (CONOPS) and spacecraft fuel budget are both sized appropriately to support the expected conjunction and CA high-interest event rates for your chosen orbit as well as responsibility for conjunction mitigation maneuvers during transition into and out of operational orbits.

- *Rationale: An analysis of the active satellite populations and known debris object densities at the insertion orbit and along the trajectory in the final orbit, as well as an evaluation of any orbital transits, will provide insight into the potential magnitude of mitigation actions that may be required. Recognize that, nominally, the transiting spacecraft is responsible for mitigation, and in-transit conjunction management is typically more complex and restrictive than during on-station operations. NOTE: See on-orbit phase for a discussion of operational considerations regarding transit mitigation.*

PRACTICE A-2

Ensure the adequacy of spacecraft hardware features to support safety of flight best practices

To operate satellites safely on orbit, certain satellite hardware capabilities are required. It is important to include safety features and best practices in your design criteria to approach and incorporate "safety by design" rather than waiting to address safety issues in a less efficient manner when they arise operationally.

In particular, attention should be given to the following items:

» Design satellites to have the ability to reliably and predictably maneuver for orbit management from deployment through disposal including mitigation for "late notice" conjunctions.

- *Rationale: The density of resident space objects is increasing and having the ability to actively manage large satellites will optimize safety and concerning conjunctions. The ability to actively manage an orbit is especially important if your spacecraft operates above the altitude at which human-spaceflight operations are regularly conducted (presently in the 360–450 km range). Techniques commonly employed for orbital management are chemical propulsion, electric propulsion, or differential drag.*

» Design the satellite with a large enough radar cross-section or optical visual magnitude to be tracked by your tracking authority, especially should satellite on-board navigation data processing or transmission fail during operations. If this is not possible, arrange for a supplemental position determination capability, such as an on-board beacon powered and operated separately from the main satellite bus.

- *Rationale: Having an accurate and timely knowledge of satellite position will provide situational awareness and more accurate information for conjunction management.*

» Take reasonable measures to impose satellite uplink and data security to prevent hostile commandeering of your spacecraft.

- *Rationale: Cybersecurity is an important design and operational consideration for safety to ensure you maintain control and adequate positional knowledge of your satellite(s).*

» Consider including the capability for your satellite to maneuver to a low cross-section orientation to further mitigate the risk in any potential conjunctions.

- *Rationale: The ability to orient the satellite to minimize cross-section during a conjunction further reduces the risk of a collision as many of the prediction tools use hard body radius, based on the largest radius,* *for conjunction analysis. Further mitigation by orientation provides additional margin to avoid collisions when conjunctions are identified.*

» Consider active debris removal and any necessary interfaces, once they become available, to allow for active removal of the satellite, should it become inoperable, if the satellite will occupy an orbit for which the natural decay deorbit requires significantly more than five years.

- *Rationale: As the space domain becomes more commercially vibrant, the ability to remove, either via natural decay or active means, orbiting objects that are inactive or that contribute hazards and potential conjunctions will be important to maintain the space sustainability of outer space activities.*

» Design the satellite to minimize debris creation when passivated and in the event of a collision with small debris.

- *Rationale: Minimizing the possibility for debris creation helps maintain a sustainable space environment for all operators.*

» Plan for your operations team to be reachable and responsive within the time frame required to resolve conjunctions.

- *Rationale: Timely communication between operators involved in a conjunction will ensure that appropriate, coordinated actions are taken to mitigate the risk of a collision.*

» Design the satellite for either 1) a controlled reentry or 2) to preclude any part of the spacecraft that survives reentry from impacting the Earth in excess of 15 joules and the calculated casualty risk is less than 1 in 10,000.

- *Rationale: Protecting humans from harm from objects re-entering Earth's atmosphere is paramount. A controlled reentry can direct the object over unpopulated areas. Alternatively, demisability should be maximized to the degree possible since any pieces of the spacecraft that survive reentry can potentially cause harm if impacting in a populated area. Current standards (see* NASA-STD-8719.14 *for more details) suggest that limiting kinetic energy to below 15 joules is adequate for the protection of human life, though operators should consider designing to an even more conservative value (e.g., 10 joules) to further mitigate any residual risk due to the lack of sophistication of prediction tools.*

» Implement a disposal requirement through the combination of satellite basic design, hardware reliability, or operational plans. Document a plan for operational concepts for early deorbit, including monitoring, to achieve a higher than 90% per-satellite likelihood of success in accomplishing planned disposal.

- *Rationale: It is important to establish a well-thought-out plan for satellite disposal during the design phase, prior to operations, to minimize conjunctions during the disposal process as well as ensure* *safety for the space domain and the public.*

PRACTICE A-3

Ensure the adequacy of satellite / ground system software to support safety of flight best practices

In addition to possessing the hardware features needed for safety of flight, it is important to furnish software and analytical support to use those hardware features properly.

The following analytical capabilities should be secured and operationally demonstrated via a data exchange with the CA service provider before launch, and subsequently tuned and validated after launch:

» Establish an operational interface with your choice of CA service provider ahead of launch and ensure integration between both systems satisfies the data sharing and safety considerations outlined in this document.

- *Rationale: CA service providers are a cornerstone of spaceflight safety acting as data exchange hubs for O/O. There are a variety of them, public and commercial, and regulatory and licensing constraints might impact which ones you can rely on. Do your due diligence as part of the design process and establish your interface and test functionality well ahead of launch.*

» Generate and share without restriction predicted ephemerides, which include future predicted states (position and velocity) and associated covariance matrices that realistically describe the predicted position and velocity uncertainty ("NASA Spacecraft Conjunction Assessment and Collision Avoidance (CARA) Best Practices"). Start sharing within hours of deployment until reentry or disposal is achieved.

- *Rationale: Predicted ephemerides with realistic covariances that are widely shared allow other operators to maximally plan avoidance of resulting predicted conjunctions. NOTE: Do not underestimate the amount of design work involved in the production of predicted ephemerides on an operational cadence. Think carefully about the infrastructure necessary to create predicted ephemerides on an appropriate operational cadence. For example, the prediction duration, step size, and ephemeris refresh rate may depend on the frequency of satellite internal orbital determination update, frequency of active orbital change, and maneuver decision timelines. Ideally, one should refresh ephemeris every 12 hours or faster, depending on their accuracy. In low Earth orbit (LEO), typical ephemeris point spacing is one minute or faster, although highly elliptical orbits may require a different approach (such as variable point-spacing based on true anomaly). Automation for the generation of predicted ephemerides should be considered,* *especially if frequent updates are required operationally.*

» Ensure, either by developing the capability or arranging for a third party, to provide CA screenings of your predicted ephemerides against all other shared O/O ephemerides and against a precision satellite catalogue that includes debris objects.

- *Rationale: Operators must be able to assess collision risk and determine the appropriate mitigation in house or in collaboration with a third party.*

» Design the ground system such that after receiving a conjunction alert, you can pursue all reasonable avenues to make sure that the conjunction data message (CDM)/screenings are shared between both operators to coordinate any required mitigation actions.

- *Rationale: Proactive and timely coordination in the event of a conjunction alert is important to minimize collisions and maximize space safety. If the infrastructure does not facilitate clarity and timeliness of communications, the ability to mitigate potential conjunctions is impacted.*

» Design the system to utilize the Consultative Committee for Space Data Systems (CCSDS) standards for data exchange such as CDMs and ephemerides.

- *Rationale: the CCSDS standards are a global consensus and are widely used. Utilizing an existing, widely used standard will facilitate clarity and timeliness in communications and conjunction resolution.*

B

Pre-Launch & Early Orbit

PRACTICE B-1

Create and expeditiously publish your strategy to transport yourself to your final orbit

There are several approaches to reaching a final orbit ranging from a straightforward direct injection to an extended, multistage transiting sequence. Defining and publishing the intended approach allows others to understand your intentions and facilitates the establishment of structures to help resolve any CA issues that do arise. Proprietary restrictions should be construed very narrowly; the general guideline should be if a feature or approach is discoverable after launch, then it should be shared explicitly before launch.

Specific actions to be taken in response to this practice include:

» Publish your spacecraft's intended injection orbit and the intended final orbit. If these are not the same, describe the strategy your spacecraft will use to transit from the injection orbit to the final orbit to the degree possible; an example could be: approximately four weeks of increased circularization through regular, frequent low-thrust burn typically achieving 6 km/day in semi-major axis increase, or intentional pauses in ascent of an appropriate period to achieve proper node phasing.

- *Rationale: Providing information publicly regarding your initial and final orbit, along with the strategy that will be used to transit will facilitate coordination with operators occupying orbits that will be traversed to minimize potential conjunctions.*

» For multi-launch operators (constellations), consider publishing the launch cadence, number of satellites per launch, and first and last launch epoch projection to the degree possible.

- *Rationale: Providing information publicly will facilitate coordination and allow other operators to have maximal situational awareness for design and operational optimization to reduce potential conjunctions.*

» Establish, well in advance of launch, nondisclosure agreements (NDAs) and/or memoranda of understanding (MOUs) with any operators where the transit trajectories will intersect any major constellations of satellites so that needed information exchange and coordination to facilitate safe crossings through these constellations can take place.

- *Rationale: Coordinating transit through constellation orbits as early as possible will maximize operational efficiency for both operators and minimize the potential for conjunctions.*

» Operators of transiting satellites, as the creator of new conjunctions, coordinate with on-station satellite operators.

- *Rationale: For conjunctions involving transiting satellites, ethical designation of maneuver responsibility should seek to avoid creating hardship for the on-station satellites performing their mission. The guideline is not designating who maneuvers but who is granted greater say in which party maneuvers. While the burden of maneuvering could then fall to the transiting satellite, more agile operators or heavily automated systems may prefer to handle maneuvering around the transiting satellites with sufficient coordination established.*

» Publish basic information about your satellite required to enable the CA process. This would include basic size information (so that a reasonable hard-body radius can be set for CA calculations) and whether the satellite can actively change its orbit (through propulsion or differential drag). If anomalies affect your satellite's ability to maneuver for CA, update your satellite's publicly accessible information to reflect this so that other O/Os will recognize that they will bear the mitigation responsibility for any conjunctions with your satellite. (See Appendix A for a list of suggested information to make available.)

- *Rationale: Publicly providing a minimum set of characteristics about your satellite enables greater situational awareness on the part of all operators and subsequently more informed planning for collision avoidance.*

» Register your satellite with your appropriate registry and include operational contact information (phone, email) and if necessary, ensure that the registry makes the information available to all other operators.

- *Rationale: It is extremely important that satellite operators have a way to contact each other in a timely fashion to resolve CA issues that require coordination between O/Os.*

» Respond to high-priority and time-sensitive coordination in a timely manner, particularly in the case of an emergency (imminent) conjunction that requires immediate attention.

- *Rationale: Responsiveness to high-priority and time-sensitive communication is critical in resolving potential conjunctions and avoiding collisions.*

PRACTICE B-2

Perform launch collision avoidance (LCOLA) against all resident space objects with special consideration for crewed space assets

Launch collision avoidance (LCOLA) is the screening of predicted launch trajectories against resident space objects to determine conjunction risks and choose launch times that minimize these risks. LCOLA screening is essential to protect crewed space vehicles and helpful to expose early mission collision risks, especially in the denser populated regions of LEO.

Particular practices in the conduct of obtaining optimal launch collision avoidance screenings include the following:

» Ensure that the screening authority obtains predicted ephemerides for crewed vehicles and includes all available owner/operator predicted ephemerides Many satellite owner/operators and NASA regularly provide predicted ephemerides to the U.S. Space Force (currently) for satellites, crewed orbital and visiting vehicles. Satellite owner/operators and crewed vehicle operators must produce and make widely accessible such ephemerides that include planned maneuvers to ensure the most accurate predictions are used for screening.

  - *Rationale: Satellite and crewed vehicle ephemerides are required for an appropriate launch COLA screening effort that adequately identifies launch and deployment collision risks and protects crew safety.*

» Perform launch collision avoidance screenings against all resident space objects and crewed vehicle using both screening authority generated ephemerides and owner/operator ephemerides. Choose launch times after assessing the relative risk levels across the overall launch window. Lacking any other information about the crewed vehicle, use the standard NASA screening volume of 50 km radial x 200 km in-track x 50 km cross-track. Close any launch windows for which the predicted launch ephemeris penetrates this screening volume.

  - *Rationale: Crew safety is paramount, and operators should not launch into situations that puts crew safety at risk.*

PRACTICE B-3

Coordinate with your cataloguing entity before launch and provide facilitating products during launch and early orbit

Cataloguing newly launched objects is often difficult, especially when a large number of satellites are deployed simultaneously. Individual orbits need to be fit to each object, and then the particular satellite identities must be attached to each of these orbits.

The following O/O actions can substantially assist with this process:

» Establish with the cataloguing entity a set of either temporary or permanent cataloguing numbers for the launch.

- *Rationale: Obtaining catalog numbers as soon as possible, even if temporary, will facilitate information exchange about ephemerides as soon as possible.*

» If possible, request post-deployment state(s) from launch provider and propagate and submit to screening authority for CA screening and use in reducing cataloging timelines.

- *Rationale: Reducing the uncertainty of satellite position post-launch and providing ephemerides to the screening authority as soon as possible reduces the potential for collisions.*

» Generate post-launch ephemerides for your satellites, and (as quickly as possible with a goal of <12 hours post-deployment) furnish them to the cataloguing agency.

- *Rationale: Publicly distributed TLEs are not sufficient for this purpose, and the post-launch ephemerides will help to validate the early cataloguing results and allow specific spacecraft identities to be assigned to the candidate orbits that the cataloguing entity has produced.*

» Prioritize rapid spacecraft commissioning to facilitate rapid submission of reliable spacecraft ephemerides to the CA screening authority, even if this can be done only with temporary satellite numbers. This reduces the so-called "COLA Gap" delay between launch and the start of the CA enterprise caused by the time required for cataloguing, since these ephemerides can be used for CA screenings.

- *Rationale: It is important to get information about satellite state as soon as possible to facilitate coordination with other operators, especially during initial operations and until assets are in stable orbits.*

C

On Orbit

PRACTICE C-1

Maintain quality O/O predicted ephemerides and spacecraft status information and submit/update this information regularly to the CA screening authority

The space domain is a dynamic environment in which both space weather developments and O/O active trajectory management affect the accuracy and precision of satellites' future states. To be meaningful, CA screening results must reflect the best estimates of these future states. Additionally, knowledge of a satellite's current CA status, meaning the satellite's ability to produce ephemerides and take CA mitigation actions, is important for informed CA risk assessment. Finally, to enable the CA risk assessment process, the screening results enabled by this information must be received and processed.

» Generate accurate and precise predicted ephemerides for your spacecraft, which need to model any planned trajectory changes (by whatever means your spacecraft employs).

- *Rationale: Providing precision and timely predicted ephemerides that contain planned trajectory changes and realistic covariances allows other operators to proactively plan to avoid future conjunctions. Accurate ephemerides remain within prediction error tolerances at typical mitigation action commitment points. Precise ephemerides have realistic covariances associated with each ephemeris point. An ongoing assessment of covariance realism is necessary to maintain and provide precise predicted ephemerides. Recommended ephemeris characteristics (e.g., point spacing, regularization, propagation interval), as well as methods for testing covariance realism, can be found in* "NASA Spacecraft Conjunction Assessment and Collision Avoidance (CARA) Best Practices Handbook."

» Submit your spacecraft's predicted ephemeris regularly to your CA screening authority and if not otherwise happening, ensure that the CA screening authority makes the information available to all other operators. Submitted ephemerides should overlap with previous submissions, such that a continual, overlapping ephemeris is available to the screening authority without a gap in state information. The frequency with which ephemeris updates and submissions are needed varies with orbit type, but generally at least three times a day for LEO and daily above that altitude. However, depending on the propagation accuracy, number of objects in and transiting the orbital shell, and solar activity, consider submitting three times a day. Additionally, ephemeris updates and resubmission should occur whenever the vehicle's intended orbital trajectory has changed.

- *Rationale: Providing timely updates for predicted ephemerides, especially for planned maneuvers, that are available to all space operators allows all operators to proactively plan to avoid future conjunctions. Frequent updates are necessary to ensure that factors such as atmospheric drag, solar weather fluctuations, or unexpected trajectory adjustments are clearly and broadly communicated to all space operators. Furthermore, access to a continuous ephemeris, with no gaps in state information, allows a clearer assessment of the evolution of a conjunction to inform maneuver decisions.*

» Generate a predicted ephemeris that contains all trajectory changes that you wish to implement and submit it to the screening authority as soon as possible. If performing the screening yourself, use a higher level of conservatism in predicting potential collisions post-maneuver to account for the lack of comprehensive up-to-date information about other vehicles.

- *Rationale: Screening predicted ephemerides which include all trajectory changes ensures that the maneuver does not create high-risk conjunctions that cannot be subsequently mitigated.*

» Update your spacecraft's CA status with your CA screening authority whenever this status changes. "Status" here does not refer to the present state of the satellite's mission capabilities, which can and should remain proprietary information, but only 1) to the ability to produce and submit an ephemeris for the satellite and 2) to the satellite's ability to take CA mitigation actions.

- *Rationale: The updated information is extremely helpful to the CA risk assessment and mitigation planning activities of other active spacecraft that may find themselves in conjunction with yours.*

» Receive and process all the CA screening information generated for your spacecraft by your screening provider and use it to perform CA risk assessment.

- *Rationale: Constant CA risk assessment is necessary to determine whether conjunctions require mitigation and allow time for coordination with other operators as appropriate.*

PRACTICE C-2

Perform CA risk assessment to identify high-risk conjunctions that require mitigation

CA screening results merely identify potentially worrisome close approaches; it is necessary to examine these results to identify any high-risk conjunctions, principally in terms of collision likelihood but with the additional consideration of collision consequence.

» Use the probability of collision (Pc) as the primary collision likelihood evaluation metric.

- *Rationale: While there are known issues with the Pc and alternatives have been proposed in the research community, at present the Pc is an industry-accepted metric that achieves an acceptable balance between serious event detection performance and tolerable false alarm rates.*

» Examine the supporting data in the CDM for conjunctions that exceed a high-risk threshold or appear to have a propensity to do so, as well as other ancillary information (such as space weather forecasts), to determine whether these data are of a quality and expected stability that can serve as a reasonable basis for CA risk assessment.

- *Rationale: Because there are no foolproof methods or parameters for calculating conjunctions, it is important to examine supporting data to determine whether the quality of the CDM and the predicted conjunction merits mitigation. For example, for those that receive information from either 18th/19th or the Office of Space Commerce's Traffic Coordination System for Space (TraCSS) the* "NASA Spacecraft Conjunction Assessment and Collision Avoidance (CARA) Best Practices," *Appendix P, gives a detailed treatment of appropriate examination approaches and accompanying thresholds that can be used to render such a determination for CA information.*

» Create an internal process that identifies and flags situations that require further attention such as potential collisions, active response, and coordination with other operators.

- *Rationale: The number of potential conjunctions, and hence CDMs, that an operator may receive can be large. An internal process will act as a filter to draw attention to those situations where more attention to detail and coordination may be warranted.*

» Arrange for mitigation actions for conjunctions that, at the point at which a mitigation action must be committed, possess a Pc greater than 1E-04 (1 in 10,000) and are based on actionable supporting data.

- *Rationale: 1E-04 (1 in 10,000) is an industry-accepted metric that achieves an acceptable balance between the need to perform risk mitigation actions and tolerable false alarm rates.*

» Consider pursuing a mitigation action at a more conservative Pc level (e.g., 1E-05) or on the basis of a more conservative likelihood assessment technique (e.g., a Maximum Pc technique such as that proposed by S. Alfano in 2005[1]) if a conjunction is likely to produce a large amount of space debris (more than 50 pieces fragments) should it result in a collision.

- *Rationale: In cases where the consequences of a collision are likely to produce a large amount of space debris, risk mitigation driven by more conservative data to reduce the likelihood of a collision is warranted.*

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1 S. Alfano, "Relating Position Uncertainty to Maximum Conjunction Probability," Journal of the Astronautical Sciences, Vol. 53, No. 2 (April-June 2005), pp. 193-205.

PRACTICE C-3

Pursue adequate mitigation actions to avoid high-risk conjunctions

When indications of a high-risk conjunction are encountered, it is important to plan for a mitigation action that will both reduce the risk for this principal conjunction to acceptable levels and avoid introducing through the trajectory change any other high-risk conjunctions. Additionally, when the secondary object is also an active spacecraft, it is important to pursue outreach and coordination activities with the other O/O to allocate responsibilities for the mitigation of the conjunction.

» Identify a mitigation action that will reduce the Pc for the high-risk conjunction at least 1.5 orders of magnitude below the Pc mitigation threshold; for example, if one is using a mitigation threshold of 1E-04, it is desirable to choose a mitigation action that would reduce the Pc to 3E-06 or lower.

  - *Rationale: The recommendation states the least conservative approach; previous studies have indicated that for most satellites, risk reduction to this level will prevent any appreciable level of long-term accumulated conjunction risk.*[2] *If lower mitigation thresholds are used, mitigations actions that reduce the Pc less than 1.5 orders of magnitude below the Pc mitigation threshold may be sufficient.*

» Ensure that the selected mitigation action does not create any additional conjunctions that both exceed the high-risk threshold and that cannot subsequently be mitigated. A typical practice is to ensure that no such conjunctions exist for the 48-hour period following the time of closest approach (TCA) for the principal conjunction, although it is certainly permissible to create such conjunctions if the O/O is willing to perform subsequent mitigation action(s) to address them should they remain high risk. (48 hours is not a hard limit, but is grounded in a seven-day screening period and the balance between data acquisition and time thresholds for taking warranted action.) Submit a predicted ephemeris that contains the planned maneuver for screening; the results will indicate whether the risk for the principal conjunction has been decreased sufficiently and whether the maneuver introduces other conjunctions of concern.

  - *Rationale: Before performing a risk mitigation maneuver it is important to determine if the planned maneuver will create additional, unforeseen conjunctions in the future. If so, the maneuver can be re-planned or the operator can prepare to mitigate the subsequent conjunctions immediately.*

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2 Hall, D., "Determining Appropriate Risk Remediation Thresholds from Empirical Conjunction Data using Survival Probability Methods," 2019 AAS/AIAA Astrodynamics Specialist Conference (Paper #19-631), Portland, ME, August 2019.

- Reach out to the O/O of any secondary objects that are active payloads predicted to be involved in a conjunction because of a planned maneuver to determine whether the secondary has the ability to make trajectory changes. If it does, coordinate with the other O/O on a response to the conjunction event.
    - *Rationale: If conjunctions with another O/O with active payloads are frequent or expected to be frequent, it is advisable to work out coordination logic flows and courses of action in advance so that assembling a coordinated response in the nexus of an event is straightforward. Be prepared to collaborate with other operators via NDAs, for example, to share information about autonomous systems and maneuvering paradigms. Registering your own points of contact with your screening authority can facilitate this coordination.*
- Execute the planned mitigation action if the collision risk remains above the defined mitigation threshold at the mitigation action commitment point.
    - *Rationale: Mitigation action is recommended for conjunctions above the collision risk threshold. In addition, the community will expect the planned mitigation action to be executed and will have planned accordingly.*

D

Satellite Disposal

PRACTICE D-1

Actively and expeditiously manage the deorbit of LEO satellites that are reaching the end of their useful mission life

Inoperable spacecraft—that is, intact spacecraft that are no longer capable of active orbital safety activities—pose a substantial risk to the sustainability of space activities because they can produce very large amounts of space debris from a collision with another space object, yet can take no action to prevent such an outcome should a high collision risk be identified. It is thus very important that as spacecraft approach the end of their useful life, specific actions be taken to remove them from populated and desirable orbit corridors. In LEO this is accomplished through satellite deorbit.

The following practices outline the activities and timelines required to remove aging satellites from orbit safely:

» Provide public updates whether your satellite can produce and share ephemerides and perform trajectory alterations so other O/O can plan accordingly. No matter how carefully satellites are designed or operated, there is a chance that they may become inoperative prior to deorbit.

- *Rationale: The actions O/O may need to take to avoid conjunctions will be dependent on the ability of the secondary satellite involved in the conjunction to maneuver and/or provide precise and timely updates of its ephemerides.*

» Actively control your satellite and perform risk mitigation maneuvers during deorbit for as long as possible. Apply standard passivation methods, unless your satellite's breakup is imminent.

- *Rationale: The preferred disposal strategy is to actively lower your satellite's orbit in a controlled manner while performing risk mitigation maneuvers for as long as possible. If there is a significant amount of time remaining in passive decay (more than one year), the satellite should be passivated by removing any stored energy that could cause an accidental breakup. Examples of stored energy include propellant tanks, batteries, momentum wheels.*

- Actively manage the deorbit of your satellite at the end of its useful life if not naturally decaying withing five years or if your satellite is above any abiding and regularly populated human-spaceflight structures. Such a deorbit scenario has the following characteristics:
    - An expeditious transit from the operating altitude to an altitude just above the point of natural breakup (this altitude varies based on the level of solar activity)
    - Conformity to all regular on-orbit CA activities during this transit, mindful of the fact that the transiting satellite assumes default responsibility for any CA mitigation actions (although coordination with the O/Os of conjunction secondaries is still necessary)
    - Coordination with the cataloguing agency before pushing the satellite into reentry to ensure against an unmanageable number of reentries, as defined by the cataloging agency, occurring contemporaneously
    - Plan on strategies to make the reentry as predictable as possible such as, for example, placing the spacecraft in a tumble at an appropriate altitude before beginning reentry to improve the modeling of the reentry progress
    - Sharing the final ephemerides or state vector of the satellite with the cataloguing agency to enable continuity of tracking
    - Providing updated ephemerides after each maneuver
        - *Rationale: Active deorbit capabilities when transiting orbits with human-spaceflight structures reduces the likelihood of collisions and ensures human safety. Satellites that are not designed for decay within five years after their useful life under a nominal operations concept become space debris and a hazard for all operators, thus active deorbit is necessary to minimize the risk to all.*

Appendix A

Practice B-1: Suggested list of shared information

Information to share with a screening authority:

- Organization name
- Planned and current operational altitudes
- Routine contact information
- Emergency contact information
- What operational satellites do you have in space?
- What is your preferred Hard Body Radius for PC calculations?
- Do you include your planned trajectory alterations (propulsive maneuvers, differential drag reorientations, etc.) into your propagated ephemerides?

Information that is recommended for sharing and discussing with the other party to deconflict a conjunction:

- What is your primary source of CDMs?
- What is your secondary source of CDMs?
- What data was used in generating these CDMs?
- Do you generate and screen propagated ephemerides and covariance?
    - If yes, what ephemeris accuracy and how do you evaluate covariance realism?
    - If yes, at what cadence?
    - If yes, do you share your ephemerides and covariance publicly. If yes, where?
    - If yes, do you include maneuver execution error and post-maneuver position uncertainty in your ephemerides' covariances?
- Do your satellites use propulsion for maneuvers?
    - Do you also use differential drag for CA risk reduction maneuvers?
    - How do you screen orbit transit (raising and lowering) maneuvers?
    - How do you screen stationkeeping maneuvers?
    - How do you screen CA risk reduction maneuvers?
    - How quickly after maneuvers do you rescreen for conjunctions?

- Are your CA maneuvers planned and executed autonomously?
- What CA risk reduction maneuver threshold do you use? PC and/or miss distance
- What PC calculation method do you prefer?
- Relative to TCA when do you make a CA risk reduction maneuver decisions?
- Relative to TCA, when do you execute CA risk reduction maneuvers?
- How do you resolve situations in which results from one screening provider indicate a problematic situation but those from another do not?