SATELLITE ORBITAL SAFETY BEST PRACTICES

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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INTRODUCTION

For the last ten years, the pace of activities in space has dramatically 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. Now, for the first time, major operators have come together to produce a wholistic set of best practices, drawn from years of operational experience and the understanding that comes from actually working together to maintain sustainable orbits. This set of best practices can guide and improve cooperative operations in space, helping to ensure that future generations maximize the benefits of space.

In recent years, the private sector has joined with an increasing number of countries launching satellites to speed 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 that provide services ranging from imagery 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 incongruous rules.

Innovation cannot wait for what promises to be a long and arduous road to appropriate rules to govern space and operations. Guidelines and best practices for new and emerging systems are generally more effective than unbending and static regulations that can quickly become out of date and lock in aging technology. Evolving best practices can provide the flexibility necessary to upgrade older technology and develop new innovations that improve both space operations and life on the ground. The private sector has unified incentives to work together to protect the orbits where it does business. As technology improves, regulations can then be developed to better reflect a mature industry.

Recognizing the need to have a well-understood set of operational principles, safety standards, and behaviors that allow all operators to thrive, the satellite industry has worked together in several venues, both domestic and international, to discuss and document best practices or safety standards. To be sure, others have created "how-to" documents 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. Providing for a safe and efficient operation of satellite networks is in the best interest of the private sector. 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 (Collision avoidance (CA) 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 to enhance the safety and sustainability of the space domain.

All these documents above provide information with which operators should familiarize themselves. To be clear, the recommendations and guidelines cited in this document do not contradict or supersede these earlier works. Instead they are intended to provide a broader, comprehensive set of guiding principles and best practices as compared to the more detailed and nuanced recommendations in the handbooks cited above.

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 adopted. Ideally, the best practices contained herein can provide a foundation for discussions leading to a global consensus of behaviors.

Signatories:
Iridium Communications, Inc., OneWeb, and SpaceX

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A: DESIGN TIME

PRACTICE A-1: **Consider collision avoidance (CA) implications when choosing injection and final 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 final orbit, will be essentially collocated with any other maintained active payload and thus present systematic conjunctions, which are situations in which two objects will regularly and repeatedly come into conjunction and present collision risks with each other. Systematic conjunctions between two active payloads are particularly problematic for CA because of the needed coordination between the two owner operators (O/Os) for making potential mitigation decisions. Consider making minor changes to the orbit to eliminate any systematic conjunction situations; if this is not possible, reach out to the other O/O and well before launch, establish CA communication and adjudication protocols for resolving the expected regularly occurring conjunctions.

- 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.

- Investigate the active satellite populations and debris object densities at the injection orbit and along the trajectory to the final orbit if needed. Recognize that in-transit conjunction management is typically more complex and restrictive than during on-station operations and therefore ensure these can be safely resolved. If this is not possible, reach out to the other O/Os whose satellites will be encountered during transit and establish CA communication and adjudication protocols for resolving any conjunctions encountered. Understand that during transit, whether injection to a final orbit, transit during the operational phase, or transit for de-orbit, the conjunction mitigation burden falls to the transiting satellite and it is necessary to plan propulsion reserves accordingly. The rationale for this is that stationkeeping satellites have better prediction accuracy and constraints to conduct their mission, so it should be easier for the transiting satellite to maneuver around a stationkeeping satellite than the other way around.

- Conduct an analysis to determine the expected conjunction and CA high-interest event rates for your chosen orbit. Based on these rates, ensure that your CA concept of operations (CONOPS) and spacecraft fuel budget are both sized appropriately to support this event density.

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 bake in "safety by design" rather than addressing safety issues in an ad hoc manner.

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

- If your spacecraft operates above the altitude at which human-spaceflight operations are regularly conducted (presently in the 360–450 km range), ensure that your spacecraft possesses the capability to actively modify/manage its orbit; the techniques commonly employed for this are chemical propulsion, electric propulsion, or differential drag. Large satellites (non-Cube satellites) that operate both above and below 400 km also require active orbit management to avoid large debris-producing collisions with other orbital objects and allow the satellite's deorbit to be actively managed.
- The satellite should have 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.
- Reasonable measures should be taken to impose satellite uplink and data security to prevent hostile commandeering of your spacecraft.
- If the satellite will occupy an orbit for which the natural decay deorbit will require more than five years (the companies signing this document think that we should all aspire to a goal of one year), once a standard has been defined for active debris removal any necessary interfaces should be installed on your satellite to allow straightforward active debris removal of your satellite should it become inoperable.
- The satellite should be designed to minimize debris creation when passivated and in the event of a collision with large or small debris.
- Your operations team should be reachable and responsive for 24/7/365.25 conjunction mitigation coordination.
- The satellite should be designed 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 0.00001. See **NASA-STD-8719.14** for more details.
- A commonly articulated disposal requirement is, through the combination of satellite basic design and hardware reliability, to achieve a per-satellite 99% likelihood of successful deorbit.

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:

- Predicted ephemerides, which include future predicted states (position and velocity) and associated covariance matrices that realistically describe the predicted position and velocity uncertainty, should be generated and shared without restriction. 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 unusual orbits may require a different approach (such as variable point-spacing based on true anomaly).
- Either develop the capability, or arrange 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. Operators must be able to assess collision risk and determine the appropriate mitigation in-house or in collaboration with a third party.
- After receiving a conjunction alert, 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.

B: PRE-LAUNCH AND 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 here; the rule of thumb 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 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; 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.

- For multilaunch operators (constellations), publish to the degree possible the launch cadence, number of satellites per launch, and first and last launch epoch projection.

- If the transit trajectories will intersect any major constellations of satellites, establish nondisclosure agreements (NDAs) and/or memoranda of understanding (MOUs) with these constellation operators well in advance of launch so that needed information exchange and coordination to facilitate safe crossings through these constellations can take place. Transiting spacecraft should assume the responsibility for performing mitigation actions to avoid other satellites that are in their main operational orbits.

- 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.

- Register your satellite with your appropriate registry and **include operational contact information (phone, email)**. The latter is extremely important for resolving CA issues that require coordination between O/Os.

- Plan to respond to high-priority and time-sensitive coordination 24/7/365.25.

PRACTICE B-2:
Perform launch collision avoidance (LCOLA) against 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. There is debate within the broader space community regarding the value of LCOLA conducted against the broader space catalogue, especially debris; but there is unanimity regarding its importance for the protection of crewed space vehicles.

Particular practices in the conduct of this screening include the following:

- Ensure that the screening authority obtains predicted ephemerides for crewed vehicles. For example, NASA regularly provides predicted ephemerides to the U.S. Space Force (currently) for the ISS and crewed visiting vehicles. Crewed vehicle operators must produce and make widely accessible such ephemerides if they wish all space actors to be able to perform screenings against them and thus protect their crewed vehicles from collisions.
- Perform launch collision avoidance screenings against crewed vehicle ephemerides. 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.

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 is 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. Ephemerides can be assigned to temporary numbers as a way to facilitate information exchange.
- Generate post-launch ephemerides for your satellites, and when these ephemerides become reliable (as quickly as possible), furnish them to the cataloguing agency. Publicly-distributed TLEs are not sufficient for this purpose as 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.

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 precision predicted ephemerides for your spacecraft, which need to contain both planned trajectory changes (by whatever means your spacecraft employs) and realistic covariances associated with each ephemeris point. Recommended ephemeris characteristics (e.g., point spacing, regularization, propagation interval), as well as methods for testing covariance matrices for realism, can be found in the "**NASA Spacecraft Conjunction Assessment and Collision Avoidance (CARA) Best Practices**," Section 6.1 and Appendix I.

- Submit your spacecraft's predicted ephemeris regularly to your CA screening authority. The frequency with which ephemeris updates and submissions are needed varies with orbit type, but generally at least three times a day below 500 km 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 takes action to change its orbit.

- Generate a predicted ephemeris that contains that any trajectory change 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 postmaneuver to account for the lack of comprehensive up-to-date information about other vehicles. In both cases it is important to ensure that the maneuver 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. This 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. As a point of reference, the 18th/19th Space Defense Squadron performs batch screenings three times per day (every eight hours) and ad hoc screenings for submitted ephemerides that contain trajectory changes.

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. 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. 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 that is provided by the 18th/19th Space Defense Squadron.

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

- Plan / 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.

- 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.

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. 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]

- 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. To determine this definitively, 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.

- Reach out to the O/O early in the mitigation planning period if the secondary object is an active payload 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. Registering your own points of contact with your screening authority can facilitate this coordination. If conjunctions with this O/O 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.

- Execute the planned mitigation action if the collision risk remains above the defined mitigation threshold at the mitigation action commitment point.

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.

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 the space environment 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 particular practices outline the activities and timelines required to remove aging satellites from orbit safely:

- No matter how carefully satellites are designed or operated, there is a chance that they may become inoperative prior to deorbit. Consequently, so that other O/Os can plan accordingly, in such a situation the O/O should update publicly whether the satellite can produce and share ephemerides and perform trajectory alterations.
- If a satellite's operating orbit is below the altitude of abiding and regularly-populated human-spaceflight structures and is expected to decay fully within five years (with a goal of one year), no active management of the satellite's lead-up to natural reentry is required.
- Avoid the need to perform controlled reentry by designing your satellite to be immolated completely during reentry. In addition, all standard passivation methods should be applied prior to reentry (ref: FCC-18-159A1).
- If your satellite's operating altitude is above that of any abiding and regularly populated human-spaceflight structures or if your satellite at the end of its useful life will not fully decay naturally within five years (with a goal of one year), then an actively-managed deorbit of the satellite is required. Such a deorbit scenario has the following characteristics:
    - An expeditious transit from the operating altitude to an altitude just above the point of natural decay (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 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