National Aeronautics and Space Administration

Headquarters
Washington, DC 20546-0001

Reply to Attn of:

NASA Comments
Federal Communications Commission
IB Docket No. 18-313, Mitigation of Orbital Debris in the New Space Age
(October 30, 2020)

NASA offers the following comments and observations outlined below to the Federal Communications Commission (FCC) Further Notice of Proposed Rulemaking (FNPRM) adopted on April 23, 2020, on additional amendments to its rules related to satellite orbital debris mitigation. The FCC's FNPRM seeks comment on the following topics: probability of accidental explosions; collision risk for multi-satellite systems; maneuverability requirements; post-mission lifetime; casualty risk; indemnification; and, performance bonds tied to successful spacecraft disposal. Each topic is summarized below, with some examples of the issues raised in the FNPRM.

Probability of Accidental Explosions

- *Referencing the revised U.S. Government Orbital Debris Mitigation Standard Practices (ODMSP) 2-1, the FCC seeks comment on incorporating into its existing rules a requirement that applicants demonstrate that the integrated probability of debris-generating explosions for all credible failure modes of each spacecraft (excluding small particle impacts) is less than 0.001 (1 in 1,000) during deployment and mission operations.*

NASA comment: Regarding potentially explosive devices, NASA has an existing requirement STD-8719.14b, requirement 4.4-1, to limit the probability of accidental explosion during mission operations and passivate in order to limit probability of accidental explosion after end of mission. The requirement addresses systems and components such as range safety systems, pressurized volumes, residual propellants and batteries. Having said that, calculating probability statistics would be dependent on operating conditions and failure modes requiring extensive (likely destructive) testing. For some subsystems (i.e., battery packs), there are existing procedures in place, but demonstrating compliance for all potentially explosive devices will require regular and extensive testing even though they are likely designed not to explode under typical operating conditions. This extensive testing raises cost considerations.

Total Probability of Collisions with Large Objects

- *The FCC seeks comment on how to analyze collision risk with large objects for multi-satellite systems in non-geostationary orbits, and, in particular, for large constellations, referencing ODMSP 5-1. The FCC notes that absent any additional analysis, consideration of collision risk on a per-satellite basis may not adequately address the ultimate probability of collision for larger deployments.*
    - *Seeks comment on factors that could be considered in performing the analysis, including metrics or thresholds that would provide additional certainty to applicants regarding the FCC review process.*
    - *Seeks comment on a threshold or "safe harbor" approach, for example, where if a particular system-wide collision probability metric or other metric is exceeded, would*

trigger further review. Alternatively seeks comment on bright line rule, and on metrics for either approach.

- *Seeks comment on how to incorporate analysis of reliability or failure rate of any maneuvering capabilities into the Commission's review of collision risk.*
- *Seeks comment on methods for calculating total probability of collision taking into consideration replacement/replenishment satellites.*

NASA comment: NASA recommends constellations of satellites be treated differently from individual satellites such that a more stringent conjunction risk mitigation threshold be used for constellations. NASA recommends using a threshold for mitigation value of 1E-05 for constellations. This approach is in line with the current practice of at least one of the large constellation operators already operating spacecraft. NASA's recommendation for the definition of a constellation is a unit of twenty-five satellites.

Multiple satellite systems introduce new challenges for safety and space asset protection. Writing requirements for orbital debris mitigation should be focused on the impact of significantly increasing the number of orbiting objects in combination with the significant increase in satellites that operate in a much more autonomous manner than traditional satellites.

The present comment focuses on the following statement contained in the FCC solicitation's section addressing maneuver reliability assessments: "The Order specifies that for individual satellites, the probability of collision with large objects may be deemed zero, absent evidence to the contrary, during any period where the satellite is capable of maneuvering to avoid collisions." During the review cycle for the original Order, NASA submitted a comment outlining that such an assumption must be used with caution because active collision avoidance (CA) still leaves residual risk, the amount of which being a function of the risk level at which the owner/operator pursues mitigation action and the degree to which mitigation actions reduce the risk. In the case of large constellations, however, this assumption encounters substantial strain and constitutes an example of "evidence to the contrary" in the published Order. Below NASA clarifies why we believe this and illustrates the point with simulation results based on NASA Conjunction Assessment Risk Analysis (CARA) empirical conjunction data.

To begin with a very simple example, when tossing a coin, the probability of getting heads is 1 in 2. What is the probability of getting at least one head in four tosses? One can make a tree diagram and establish that the only way in which this will not happen is to get four tails, which is a 1/16 probability, so the probability of at least one head is 1 – 1/16, or 15/16—this is the "cumulative probability" of getting at least one heads over four tosses. For more complex situations, it becomes too difficult to make these diagrams; fortunately, there is a formula for calculating cumulative probability (derived from DeMorgan's Law of Complements; for a proof and extended discussion in a CA context see Frigm *et al.*, 2015):

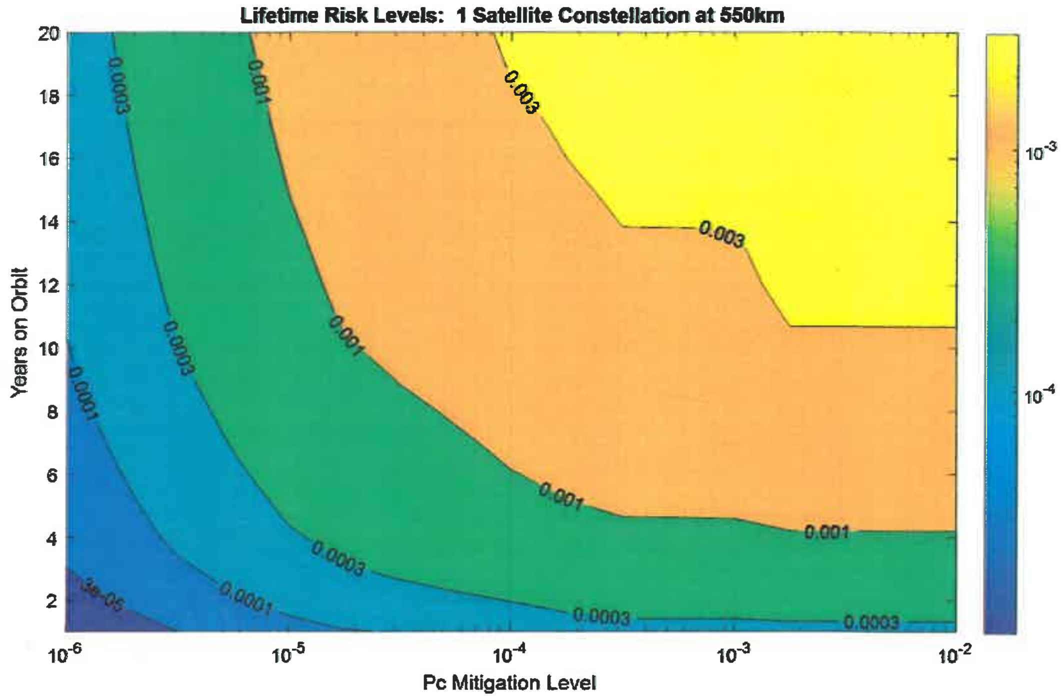
$$P_{cum} = 1 - \prod_{i=1}^{n}(1 - P_i)$$

Indeed, $1 - (1 - 1/2)^4$ gives 15/16, our earlier answer.

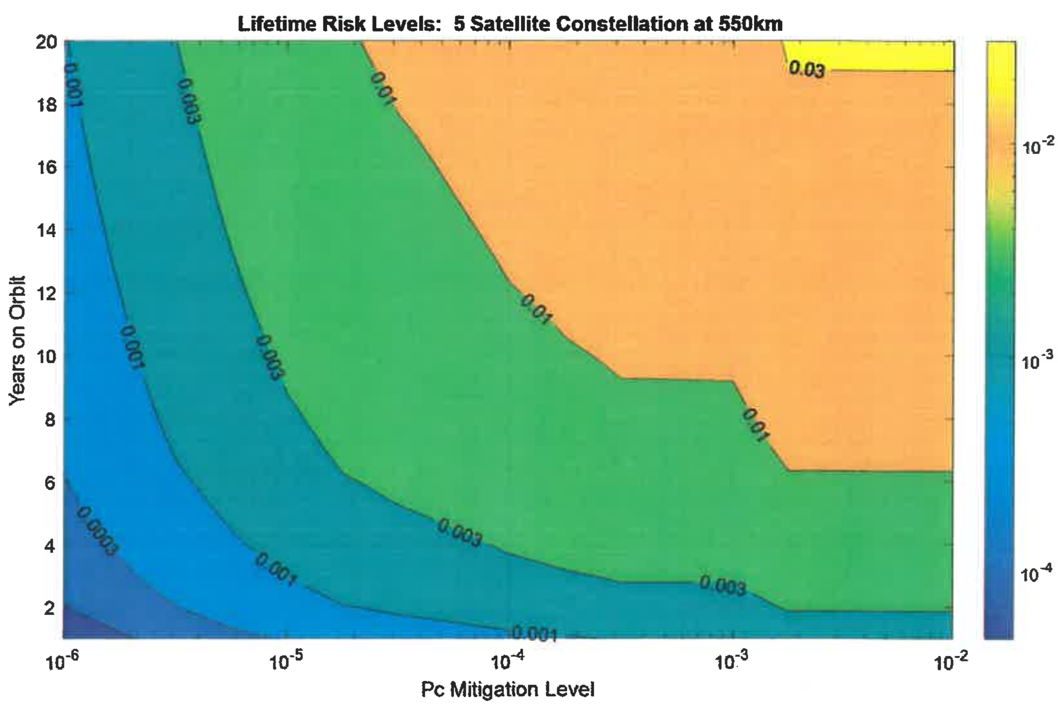
Returning to CA, let us suppose that an owner/operator is performing active CA and mitigates any conjunction with a probability of collision (Pc) greater than 1E-04, the most common mitigation threshold presently in use in the industry. For CA events with a Pc > 1E-04, a maneuver will be executed to lower the Pc to a small value. For CA events just below this threshold, however, that level of risk will be accepted because a maneuver will not be planned and executed; and the risk of such situations will compound over time. Let us say that a satellite experiences five close approaches with a Pc value (at the mitigation action commitment point) of 8E-05. No actions will be taken, so these five instances of 8E-05 will compound; and using the cumulative probability formula above, the accumulated risk is 4.0E-04, significantly higher than each individual conjunction's risk and, collectively, over the limit for mitigation. The purpose here is not to debate whether this sort of cumulative analysis should be used for individual satellites but, rather, to observe that this same sort of compounding probability is in play as a constellation grows in size. The answer to the question "what is the likelihood of at least one satellite in a constellation colliding with a large, tracked object?" is a function of the size of the constellation as well as the accumulating risk for each individual satellites; the accumulation formula above works both to accumulate the risk of successive events for a single satellite and the combined accumulated risk for a number of satellites.

To get a sense of the role that this accumulation plays, NASA CARA ran a series of simulations to show this effect for a constellation similar to Starlink. A full treatment of this approach is documented in Hall (2019), but an abbreviated description can be given here. Actual conjunction histories from payloads protected by CARA can be obtained for satellites in the 500-600km altitude regime and can be used to generate representative series of CA events, with the statistically appropriate density of different event risk levels. One can simulate mitigation by reducing any events with Pc values higher than the mitigation threshold by the amount that a risk mitigation maneuver typically would—usually 1.5 orders of magnitude, which is a factor of about 0.03. A hard-body radius (HBR) of 10m to represent the two conjuncting satellites' combined size and a maneuver commitment point of 8 hours before the time of closest approach (TCA) of the two objects were both used. Constellation lifetimes from 1 to 20 years were considered. 1000 trials of different event histories were assembled, with the median values used to populate the results graphs.

The graph below gives cumulative risk results for a single satellite at ~550km. The x-axis gives the Pc threshold at which mitigation actions will be taken, the y-axis gives the number of years on orbit (which determines the amount of exposure to conjunction events), and the contours/colors indicate the lifetime risk experienced. If one wishes to use the NASA Orbital Debris Program Office (ODPO) 0.001 lifetime risk requirement as a benchmark here (this is not in fact a proper use of this requirement, but more will be said about this later), that contour is given by the boundary of the green and orange color swaths (labeled as 0.001). One can see here that, if one wanted to meet that requirement for a six-year on-orbit lifetime, pursuing mitigation actions for events that exceed a Pc level of 1E-04 is necessary; for a sixteen-year orbital lifetime, a mitigation Pc level of ~1E-05 would be required.



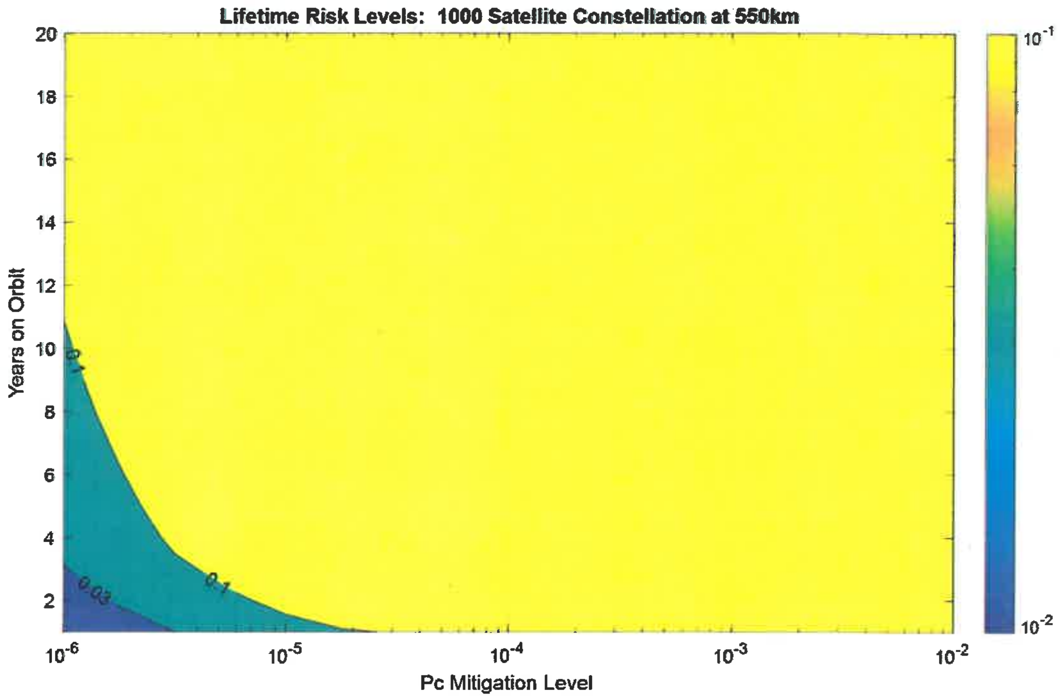
As the size of a constellation is increased, accumulated risk increases as well. For a five-satellite constellation, in which the lifetime risk of at least one satellite collision is considered, the equivalent graph is the following:



Here the ODPO requirement contour is now between the blue and aqua colors (labeled 0.001), and one sees that it cannot be met at all at a mitigation level of 1E-04 and for constellation lifetimes of only about

3 years at a mitigation level of 1E-05. The requirement could be met for a 20-year on-orbit lifetime at a mitigation level of 1E-06, which is a demanding remediation level.

The results for a 1000-satellite constellation are given below; for any reasonable time on orbit and mitigation threshold, the odds of at least one collision during the orbital lifetime are greater than one in ten:



These results are hardly encouraging and in fact are dispiriting—it would seem that there is nothing that can be done to avoid collision. How should a regulatory body respond?

It is important to recognize the difference between probabilities of collision calculated from debris flux models (NASA ODPO) and those calculated from actual orbital solutions (NASA's CARA program). The ODPO calculation considers the possibility of collision over a specified time period presuming there are no mitigation actions taken, but its answer is a true probabilistic risk (to the limits of the modeling, which makes certain assumptions about the stochastic interactions of satellites). The CARA calculations provide *perceived* risk, meaning, for each conjunction, the likelihood that the miss between the objects will be smaller than their combined size, given the limitations of the orbital information supplied. In point of fact, the actual (God's eye) risk of collision for every actual conjunction is either one or zero—either the satellites will actually collide, or they will not—and if NASA had nearly continuous, very precise orbital data on both objects and nearly perfect orbit update and prediction models, the probably of collision for nearly every conjunction would be zero. This means that the levels of perceived risk are really a function of the quality and frequency of the available orbital data and our ability to predict future atmospheric density and thus reduce propagation error.

This fact bears repeating and some reflection: in almost all cases, high Pc values for actual conjunction events are due to the uncertainty and sparsity of the satellites' tracking data, shortcomings in dynamical models, and inability to predict tomorrow's atmospheric densities. Of course, mixed into that data pool are a few situations that constitute actual collisions, so it is necessary to mitigate when presented with data that indicate, based on what is known about the conjunction, a high-risk situation. But lifetime risk values calculated from conjunction histories are to a large degree a reflection of the capabilities of the tracking and modeling; and given this, it is difficult to define precise requirements for this type of lifetime risk value. The ODPO requirement of 0.001 lifetime risk of collision with large objects is not fully complete because it does not consider the effects of active CA mitigation actions; and a lifetime collision risk number derived from conjunction histories is not complete either because it is based on a particular tracking data and modeling solution and thus not independent from system improvements. Furthermore, the two are not commensurate—it would not make sense to take the ODPO 0.001 requirement, derived from flux analysis, and apply it to lifetime risk values obtained from analysis of conjunction histories. To determine a durable requirement for lifetime collision risk from conjunction history data would require an extended, dedicated study. This is perhaps an item that the Department of Commerce can investigate and underwrite should they be given formal space traffic management authority. For the present, our observations and recommendations are the following:

- While accumulated risk can perhaps be ignored for individual satellites that have propulsion and perform CA, for constellations even rather small in size accumulated risk is a real issue that must be addressed.
- As such, constellations of satellites should be treated differently from individual satellites. Our recommendation for a number-of-spacecraft threshold to define a constellation that should be considered as a unit is twenty-five satellites. It was shown in the above graphs how much a constellation of even five satellites increases accumulated risk beyond that for just a single satellite. This number is consistent with our constellation definition recommendation given as part of the FCC mandatory propulsion question, addressed in the next section.
- In the absence of a definitive study to establish appropriate lifetime risk levels based on analyzing conjunction events (and thus being able to account for mitigation actions), NASA recommends a more stringent conjunction risk mitigation threshold be used for constellations. A reasonable modification to threshold conservatism would be an order of magnitude increase: if the industry-standard threshold for mitigation of 1E-04 was intended to be used (and this should probably be a more general recommendation by the FCC, for merely possessing a propulsion system but performing mitigation actions only for conjunctions with a Pc greater than, say, 1E-01 is unlikely ever to result in a mitigation action and probably provides no additional safety at all), a constellation's using a value of 1E-05 is an appropriate response. This approach is in keeping with the current practice of at least one large constellation operators.

Maneuverability Above a Certain Altitude in LEO

- *The FCC seeks comment on whether satellites or systems deployed above 400 km in the LEO region should have the capability to maneuver sufficient to conduct collision avoidance during the time when the spacecraft are located above 400 km. Seeks comment on alternative altitudes, and on what types of maneuverability could be deemed sufficient, including certain performance-based thresholds for maneuverability.*

NASA Comment: The FCC seeks comment to help adjudicate the balance between the expected increased safety brought by satellites' possession of propulsion systems and the additional burden this will impose on satellite construction and operation. As part of this question, the FCC asks whether a propulsion requirement should, perhaps, be levied only on constellations and whether it should be confined only to satellites with orbit altitudes higher than a specified perigee height. NASA's recommendation is to require propulsion for satellites in orbits higher than the nominal International Space Station (ISS) altitude (~420 km) but apply this requirement only to constellations larger than twenty-five satellites.

420km Perigee Height Requirement for Propulsion

There is, to be sure, a certain arbitrariness in choosing a particular orbital altitude as a boundary for requiring propulsion, with some commentators recommending altitudes essentially as high as the circular orbit height for meeting the 25-year rule by natural decay—which (conveniently) eliminates any propulsion requirement for orbits that would not need it to comply with the 25-year disposal rule. In our evaluation, however, NASA believes that the orbital altitude threshold should be essentially that of the ISS, for the following reasons:

1. This posture improves the safety of human space flight by requiring large concentrations of satellites above the ISS to be able to perform controlled deorbits until the payloads are below the ISS altitude. This reduces the need to maneuver the ISS to avoid large objects in uncontrolled deorbit, a collision with which is likely to destroy the entire Station. Such a requirement should be imposed on constellations operating higher than the ISS altitude—namely to perform a controlled deorbit, with the deorbiting object taking all responsibility for needed collision risk mitigation maneuvers, until below this altitude. The ISS is an extremely large object that is difficult and expensive to maneuver, and such perturbations often interfere with its scientific missions.
2. The ISS is expected to be supported governmentally for at least another decade, and the strong interest in government-industry partnerships allows reasonable supposition that it will be sustained well beyond that time. Because this orbit represents a compromise between ease of access (lower orbits better) and atmospheric drag (higher orbits better), its immediate vicinity is a good expected candidate orbit for future human spaceflight destinations (the Chinese space station efforts have all been below 400km). So to the degree that protection of human spaceflight plays a role in the propulsion requirement, the 420km orbital altitude is a good choice.
3. In addition, of course to the protection of human life, extended-stay human space vehicles tend to be large, relatively fragile, and very expensive. The ISS also represents a broad international investment. It is reasonable to ask space actors to accept a certain added cost in order to protect these specialized assets.
4. For satellite operations that directly support or interact with the ISS, the NASA human space flight protection entities and regulations will be engaged; because of this additional level of government oversight, NASA recommends that such activities be considered *eo ipso* to be safely operating, even though they would of course violate ISS exclusion volumes, perhaps be operating without propulsion systems at ISS altitudes, &c. The coordination of these activities with a government space safety entity (here NASA JSC Flight Dynamics Operations) will ensure that the particular activities of such satellites will conform to safety-of-flight best practices

Constellation Size Threshold of Twenty-five Satellites for Propulsion Requirement

There is a legitimate concern that an across-the-board requirement of propulsion systems above an altitude such as 400km could substantially affect scientific and academic missions; at the same time, merely increasing the altitude requirement to ~600km in order to achieve a *de facto* exemption for this class of missions is not the right answer. Instead, NASA recommends, as is suggested in the request for comment, drawing a distinction between individual and small-head-count missions, and larger constellations.

In the case of NASA's science missions, adding a blanket propulsion requirement would cause a significant hardship on the missions and principle investigators utilizing CubeSats, a growing trend to achieve valuable science. A large majority of CubeSats in development and deployment do not have the required volume, power, mass or attitude determination, and control systems to support propulsion systems with today's technology. While a waiver process is in place, it is desirable to avoid waivers becoming a common occurrence as it will impact schedule and cost. It is of value to note, many NASA science missions are University led.

As the cumulative collision probability graphs from the previous section show, the combined effects of multiple satellites accumulate quickly. Furthermore, allowing non-propulsive moderately-sized constellations (larger groups of satellites than a handful but short of the hundred- and thousand-satellite "large constellation" size) will produce a large number of uncontrolled deorbits that will cross the ISS altitude and will thus constitute a safety decrease and mission-interruption burden for the ISS and any other crewed stations in that vicinity.

NASA recommends strongly against increasing the level beyond 25. The level of 100 suggested in the articulated questions strikes us as much too large—several such constellations would provide the same overall sets of problems as a large constellation but without the added controls that propulsion systems allow.

Avoidance of ISS and Other Inhabitable Stations

As remarked earlier, avoidance of objects by the ISS and other large, inhabitable stations is a difficult exercise, and in any such close approach there is residual risk of loss of human life. Therefore, as suggested in the solicitation, active avoidance of the ISS and other inhabited stations is important. Constellations of twenty-five or more satellites operating above 420km should be required to manage their re-entry in order to minimize the perturbations to these large, crewed vehicles. Specifically, this would mean the following:

1. Actively to manage the descent of the spacecraft below the altitude of the ISS and/or any other inhabitable stations. Preferably, this should be done through the slow, measured semi-major-axis reduction of a circular orbit rather than by decreasing perigee to produce a highly eccentric orbit, which is more difficult to model and control.
2. To perform this descent so as to remain outside of an exclusion box about each such inhabitable station of ±10km x ±40km x ±40km in the radial, in-track, and cross-track direction, which is the avoidance box presently used operationally by NASA JSC for ISS protection.

Precision Ephemeris and Realistic Covariance for Satellites above 420km

The FCC solicitation asked whether requiring owner/operators to furnish predicted future positions would be helpful to the conjunction assessment enterprise. At NASA, we have required our missions to provide this information for many years and have observed its substantial benefit. The particular virtues of owner/operators providing predicted ephemerides with covariances, which would be intended for broad circulation among all other space actors, include the following:

1. For maneuverable missions, planned maneuvers are included in the circulated ephemerides, making it possible for all other space actors to obtain a reasonable estimate of the satellite's future position. This also enables collision avoidance screenings to be conducted against the mission's planned trajectory, rather than a simple propagation of the current trajectory (which, if a future maneuver is planned, will not be the correct trajectory). Furthermore, missions that perform frequent maneuvers using low-thrust technology, with long, small-thrust burns, will not follow a Keplerian trajectory and thus cannot be reliably maintained through traditional methods; a published ephemeris is the only way to have a reasonable prediction of such satellites' future positions.

Such an ephemeris, with realistic covariances provided at every ephemeris point, is necessary for performing CA; for all probability-based methods of assessing collision likelihood require trajectory uncertainty information, which the covariance provides. NASA has developed guidelines for ephemeris production in order to render a covariance-enabled ephemeris that will properly enable CA, which we are happy to share with the FCC. Most of these guidelines are too detailed technically to be appropriate content for a higher-level rule set, but they could serve as a helpful rule-set for evaluating whether a particular applicant's ephemeris generation capability is sufficiently sophisticated to enable the CA enterprise.

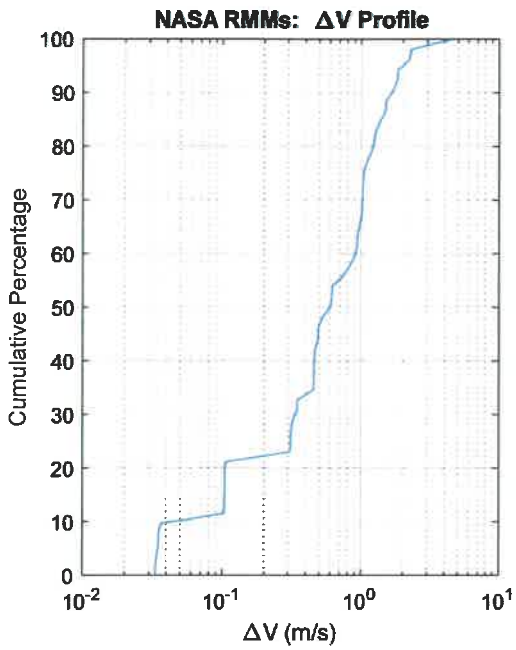
It has been asked whether the requirement to create and furnish ephemerides with covariances, especially when maneuvers are planned, should apply to satellites that employ autonomous flight control and even autonomous collision avoidance. From NASA's experience with spacecraft that employ both paradigms, we have found that it is even more important in such situations that ephemerides be produced and rapidly forwarded to a central distribution node so that they may be made available to other spacecraft operators. Among the virtues of autonomous flight control is the ability for individual satellites to perform orbit maintenance activities without active ground control involvement, allowing greater operational efficiency and reduced staffing. However, this paradigm is typically often characterized by a lack of ground foreknowledge of satellite activities—it is not unusual for maneuvers to be communicated to ground controllers well after their execution. Such a paradigm can be quite dangerous when an autonomously-controlled satellite comes into conjunction with either a traditional maneuverable active payload or, worse, a separate, autonomously-controlled satellite: those spacecraft could be planning a maneuver without any insight into what the first spacecraft is intending, and the two spacecraft could well maneuver into each other. So while autonomous flight control can be an efficient and desirable technology, it is imperative that any implementation of such technology be able to communicate quickly to a terrestrial recipient its near-term maneuver intentions (with the expectation that such intentions will be shared widely with other satellite operators, in the form of an ephemeris with the maneuver embedded in it) and include a failsafe so that ground operators can abort a planned maneuver if its safety comes into question.

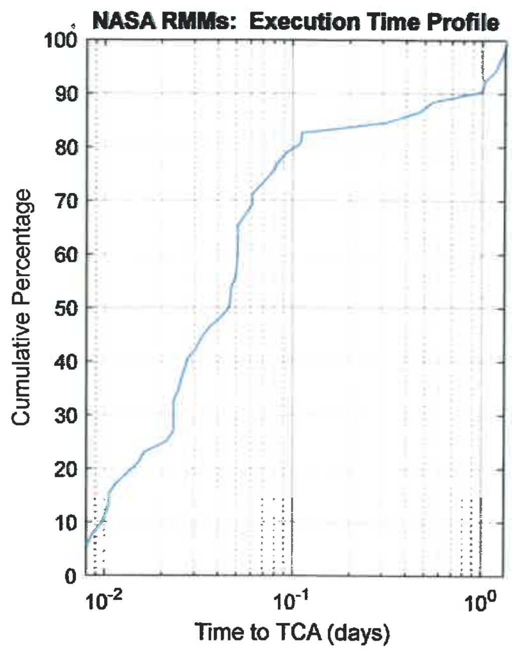
2. Non-maneuverable missions that are too small to be tracked easily and reliably by USSPACECOM, and thus will not have an accurate predicted ephemeris available as part of the USSPACECOM and/or DoC free CA service, should also produce predicted ephemerides that include realistic covariances, as specified in 1) above, in order to enable the CA enterprise on behalf of these objects.

Collision Avoidance Risk Mitigation Trajectory Alteration Adequacy

The FCC seeks comment on whether, for satellites in orbits that will require a propulsive capability, a minimum propulsive capability should be specified, and if so how such a specification should be formulated and what its particular values should be. An example is cited from an Amazon submission that proposed 5km of trajectory alteration in a 24-hour period.

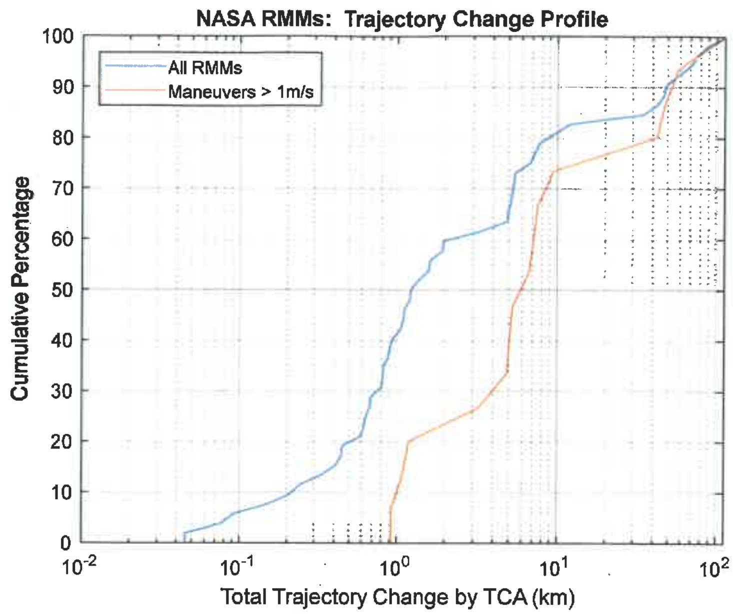
Plato pointed out that it is the nature of legislation to have to simplify situations and not be able to take account of all subtleties, and that is the case with trying to specify a requirement of this type. Spacecraft maneuvers are generally described in terms of ΔV, meaning the amount that they change the velocity of the orbit and therefore, over a finite period of time, produce a certain trajectory change. In this sense the Amazon submission is not improperly framed, as it specifies a level of trajectory change (5km) in a specified period of time (24 hours). However, when NASA profiles risk mitigation maneuvers (RMMs) that have been performed by CARA's protected missions over the last several years, it can be noted that most maneuvers are executed much closer to TCA than 24 hours. The graphs below give cumulative distribution function plots of both the ΔV of the RMMs and the execution time, the latter as time (in days) before TCA:





Some of these maneuvers are surprisingly large (> 1m/s of ΔV is considered a large maneuver); while a subset of these represent drag make-up maneuvers (DMUs) that were moved temporally in order also to mitigate a conjunction and are thus RMMs in only a secondary sense, others reflect situations in which a large amount of displacement was required in a short period of time.

It may also be helpful to look at a profiling of total trajectory changes, calculated by considering the amount of orbit displacement that took place by the time TCA was reached:



Note that some 35% of the maneuvers executed alter the trajectory more than 5km by TCA. If we plot just the large maneuvers, which we considered might be relocated DMUs, we still see several with relatively small trajectory alterations (about one-third are less than the 5km figure suggested by Amazon). Taken in an ensemble sense, these data indicate that the Amazon-recommended figure is not adequate as submitted. Instead, our recommendations are the following:

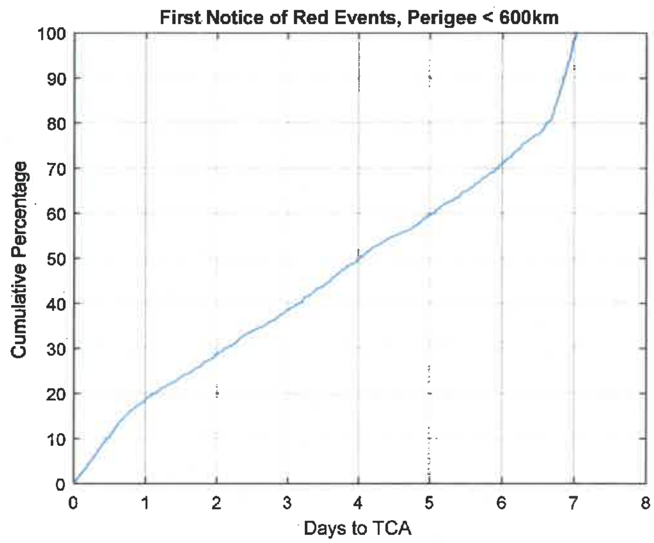
- For a "safe harbor" maneuver capability, NASA recommends the ability to perform a 1 m/s burn in relatively short time period, *i.e.,* the ability to produce ~18km of trajectory change within one orbit revolution. Essentially all chemical propulsion systems, and a number of ion thrust systems as well, should be able to meet this requirement.
- If the safe harbor requirement cannot be met, then an analysis should be required to demonstrate that, for an array of typical conjunctions for a particular orbit regime, high-risk events can be mitigated to a level one and one-half orders of magnitude below the mitigation action threshold. If a 1E-05 mitigation threshold were used, the maneuvers would need to be able to reduce the expected Pc value to ~3E-07. NASA CARA is happy to provide typical conjunction histories for different orbit regimes in order to enable such analyses.

<u>Differential Drag as Acceptable Risk Mitigation Mechanism</u>

The FCC seeks comment on the acceptability of differential drag as a conjunction risk mitigation mechanism, noting that there is some disagreement within the community regarding its adequacy. The question is not whether the approach is capable of producing sufficient trajectory change to mitigate most close approaches; it is clear that, if pursued with sufficient lead time, it should be able to produce notable changes to the in-track orbit component, which (because it changes the orbit's semi-major axis) will change the radial component, which of the three components most strongly affects the Pc. Rather, the question is the degree to which this sufficient lead time will be available, meaning the frequency with which the first indication of a "red" CA event (one with a Pc greater than the mitigation threshold) will occur far enough in the future that differential drag can be reasonably employed as a mitigation. The NASA CARA historical conjunction database can be mined to give some sense of the amount of lead-time generally available; and this, coupled with some assumptions regarding the timeliness of differential drag, can help to shape a policy decision regarding its adequacy.

NASA CARA has been performing CA for NASA missions for some fifteen years, and its collective database of Conjunction Data Message (CDM) information is often quite useful in profiling routine conjunction behavior. One such item that it is helpful to profile here is the amount of warning time that is typically available for serious conjunctions, and the way to do this is to tabulate the point before the time of closest approach (TCA) that the first indication of a red event is observed.

For this profiling, all events for NASA missions with perigee heights below 600 km (a reasonable perigee height below which differential drag might be attempted) from October 2016 to the present were examined. A red Pc threshold of 1E-04 (the most common red threshold used in the industry) and a hard-body radius of 10m (a compromise value, as the industry uses anything from 5 to 20m, depending on satellite size and desired level of conservatism) were used. The graph below gives a cumulative probability function of the "days to TCA" when the first indication of a red event occurred for the 37 protected NASA missions with perigee heights below 600km:



As an aid in reading the graph, a couple of verbalized interpretations are given here. For the (2, 30) point, the verbalized gloss would be that 30% of the red events give their first indication of red status two days to TCA or closer; for the (4, 50) point, the gloss would be that 50% of the red events give their first indication of red status four days to TCA or closer.

For satellites that employ chemical propulsion, a notification of a red event two days to TCA, although manageable, is still a somewhat uncomfortably late notice; one needs to examine the full set of risk assessment indices, determine that the event is in fact actionable, conduct maneuver planning to pick an appropriate avoidance action, create an ephemeris that includes this maneuver, perform a CA screening of the maneuver to make sure that it both mitigates the conjunction and does not create any additional high-interest conjunction events, and then actually command the maneuver. From CARA's (limited) experience with differential drag, especially at higher altitudes (~500km), probably about two days' time between the satellite's alteration of its frontal area and the TCA would be needed for at least many red conjunctions; so that would speak to a required lead time of perhaps at least 2.5 or maybe even 3 days to get the notification, determine the appropriate reorientation, generate and screen the maneuver, command the spacecraft reorientation, and allow for two days' time for the needed orbital separation to arise. We can recall multiple instances with differential drag in which no mitigation action was pursued for red events because there simply was not enough time to perform a mitigation action before TCA. As the above graph shows, more than 30% of the red events give their first notice with two days to TCA or less. As such, differential drag does not appear to be an adequate mitigation mechanism for these late-notice situations; and therefore, NASA cannot recommend it as an acceptable conjunction mitigation methodology for constellations larger than twenty-five satellites (or whatever numerical size the FCC ultimately selects) at orbital altitudes greater than 420km.

Post-Mission Orbital Lifetime

- *The FCC seeks comment on whether a rule limiting post-mission orbital lifetime is necessary if the maneuverability requirement discussed above is adopted.*
- *Referencing ODMSP 4-1, the FCC seeks comment on whether only adopting a maximum 25-year limit on post-mission orbital lifetime for LEO satellites disposed of by atmospheric re-entry would adequately incentivize non-Federal operators to dispose of their satellites "as soon as practicable." Asks whether another approach might be preferable to encourage disposal "as soon as practicable," such as by adopting a presumptive acceptable post-mission orbital lifetime of five years, for example, but allowing applicants to provide demonstrations to support longer periods.*

NASA comment: NASA Science Mission Directorate (SMD) agrees with the existence of a limit on post-mission orbital lifetime, even with the adoption of a maneuverability requirement. Creation of policy is highly desirable to prevent potential abuse, which could exist if operators are not required to remove defunct satellites from high value obits for unreasonably long periods of time.

A concern of NASA SMD is, if applied to all mission applications, decreasing the limit would impact the science achievable, limit the orbits available for scientific observation, and make waivers a common occurrence. Specific to science missions, a limit of 5-years would significantly impact all of NASA SMD's CubeSat missions which rely on natural decay of orbits to manage post mission orbital lifetime, and require nearly all missions to request a waiver, which would become costly and an added bureaucratic burden.

Decreasing the existing post mission orbital lifetime will impose greater limits on acceptable launch opportunities, associated vantage points, and ultimately the science achieved. Because post-mission orbital lifetime is directly linked to altitude, and because NASA science utilizes rideshare arrangements for the launch of CubeSat missions, the post mission orbital requirement sets the limit for which launches NASA can accept. In a rideshare arrangement, NASA does not have the choice of dictating a desired orbit, but rather is given the orbital parameters selected by the launch vehicle on which they will be riding. If a rideshare launch opportunity is going to an altitude that would have a naturally decaying orbit time greater than the requirement, NASA may be forced to decline that available launch opportunity, potentially driving storage fees until an acceptable option becomes available. Of greater concern is the amount of science that can be achieved should the requirement change for all mission applications. If reduced too much, a common outcome can be deduced that the majority of rideshare opportunities would be to ISS orbits, adversely affecting most of NASA's Earth Science, Heliophysics, and Astrophysics missions, since relevant science lies outside of this orbit.

Casualty Risk Assessment

- *Casualty Risk and Design for Demise or Targeted Re-entry. Referencing ODMSP 4-1, the FCC seeks comment on whether to adopt additional rule revisions concerning strategies to lower casualty risk, such as design-for-demise and targeted reentry. One example could be a "safe harbor" calculated casualty risk threshold of zero – achievable through either design for demise* *or planned targeted reentry, and only require additional information from applicants regarding efforts to reduce casualty risk where the calculated casualty risk is greater than zero.*

NASA Comment: Targeted re-entry seems to imply either propulsion or some other mechanism to strategically plan spacecraft demise. To adopt a zero-casualty risk threshold is only achievable if the reliability of the combined hardware and systems is 100 percent which can't be guaranteed. There could be value in such a strategy if it relaxes restrictions on high melting point materials, however, it is recommended to adopt the existing NASA criteria of less than 1 in 10,000. This provides a design-to metric at an appropriate time in the program life cycle; else, a redesign could be required to meet a zero threshold, which would be determined when the FCC license is applied for, typically at or near launch readiness when design and development is complete.

Cumulative Casualty Risk

- *Referencing ODMSP 5-1, the FCC seeks comment on how to review the cumulative casualty risk associated with larger systems to determine if such systems have in fact limited cumulative risk. Seeks comment on "safe harbor" approach, for example, wherein a system satisfying a 1 in 10,000, or other risk metric system-wide would satisfy the safe harbor threshold, such that no further analysis of risk would be required. Alternatively seeks comment on bright line rule, and on metrics for either approach.*

NASA Comment: NASA recommends Casualty Risk continue to be evaluated per-satellite. They are singular events that are unrelated. Currently, NASA does not assess cumulative casualty risk by organization, e.g., the cumulative risk of DoD satellites or NASA scientific satellites.

Indemnification

- *The FCC seeks comment on conditioning Commission authorization on indemnification of the U.S. government for costs associated with claims brought against the United States under the international outer space treaties (in particular, the Outer Space Treaty and Liability Convention). Seeks comment on whether alternative avenues to recovery are available for U.S. Government.*
- *Seeks comment on the actual costs that operators believe they could incur as a result of this requirement if adopted without a liability "cap", and on impact on innovation, competitiveness, and U.S. as jurisdiction of choice for space activities. Also seeks comment on adopting on indemnification requirement with a cap, on amount, and whether, to the extent a cap implies that the Commission is making a determination concerning the scope of risk accepted on behalf of the United States, such a determination is within the scope of the Commission's authority. Seeks comment on the availability and costs of insurance.*
- *The FCC seeks comment on whether an indemnification requirement should be implemented through license condition, or through a document provided by the licensee prior to license grant. Also seeks comment on circumstances where indemnification from non-U.S.-licensed space stations may be appropriate, such as flags of convenience.*

NASA Comment: NASA reiterates its concerns, similar to those identified by industry, about the heavy burden on small space operators such as non-profit or academic institutions associated with potential indemnification costs. Because of these unknown and likely prohibitive costs, NASA anticipates a chilling effect on the NASA Astrophysics and Heliophysics missions and NASA CubeSat Launch Initiative program which is intended to broadly promote space-based technology innovation.

Performance Bond for Successful Disposal

- *The FCC seeks comment on whether a performance bond tied to successful post-mission disposal may be in the public interest, as applicable to space station licensees. Seeks comment on adopting a requirement that space station licensees post a surety bond, similar to what they already do for spectrum use, which would be released once the space stations authorized have successfully completed post-mission disposal. Also seeks comment on whether there are alternative approaches that should be considered, such as a corporate guarantee. Seeks comment on the impact on U.S. licensing, satellite industry, and innovation.*
  - *Seeks comment on bond details and structuring for NGSO and GSO satellites, including for NGSOs whether bond would be most significant for those systems of a large mass and which would have satellites remaining in orbit for a significant number of years beyond 25 years in the event of a failure?*
  - *Seeks comment on categorical exemptions for smaller-scale systems and on whether bond could be structured in a way that would effectively exempt smaller systems as a practical matter.*

NASA Comment: Adopting a requirement that licensees post a surety bond that would be returned once post-mission disposal requirements have been met is desirable mechanism to incentivize operators to dispose of their assets. Applicability to different sizes and classes of missions is advised as it is unlikely small missions, especially academic missions, could afford a bond tied to successful disposal; they should be exempt where efforts are placed to ensure they meet deorbit requirements within other existing guidelines. Consider applicability of a performance bonds at altitudes where maneuverability requirements are levied.

NASA recommends a change in bond calculation as using mass as a metric for the bond may not meet the intent of the bond. Orbital debris risks to on-orbit assets is not simply a function of the mass of the debris. Hypervelocity impacts require very little mass to cause significant damage. The number of independent objects that make up that mass significantly impacts the risk of collision. The size of the debris field can drive the hazard presented by the on-orbit debris.

A performance bond that also considers the overall risk of harmful collisions posed by the on-orbit debris might also be considered. Regarding the significance of autonomous on-orbit maintenance, large multiple satellite systems pose an additional challenge to collision avoidance. Traditional satellites with propulsive capabilities perform periodic delta V maneuvers to maintain their mission orbit. These are planned events that are executed by an operations team on the ground. Large multiple satellite systems will likely have to rely on autonomous on-board maintenance maneuvers. Traditionally, a satellite's position is predicted by deterministic physics as is the probability of collisions. Large numbers of autonomously maneuvering satellites will make predicting the position of these satellites more challenging and therefore complicates the process of Conjunction Assessment Risk Analysis.

NASA recommends redundancy of disposal systems, updates to End-of-Mission plans and waivers in the event of a satellite anomaly or events outside of an operator's control or mission extension request which may impact post-mission disposal.

References

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