Conjunction Assessment and Deconfliction Paradigm for Co-located Satellite Constellations with On-Spacecraft "Autonomous" Flight Dynamics Control

M.D. Hejduk
NASA HQ Conjunction Assessment Chief Engineer, Aerospace Corporation
S.T. Miller; D.D. Murakami
NASA Ames Research Center
A.B. Probe; G.E. Bryan
Emergent Space Technologies
A.S. Petrov; D.B. Goldstein; E.M. Schwartz; E.P. Babcock
Space Exploration Technologies

ABSTRACT

Constellations that employ highly-automated satellite flight dynamics can operate safely from a collision avoidance (CA) perspective using current CA screening technology and communication paradigms—except when in proximity to other highly-automated constellations: there is no existing arrangement and concept of operations to allow the low-latency CA screenings, exchange of information, and assignment/acceptance of mitigation responsibility that co-location of highly-automated constellations requires. However, the serendipitous co-location of the NASA Starling mission—an autonomously-controlled technology demonstration constellation—and the SpaceX Starlink constellation has presented an opportunity (indeed, a requirement) to develop and build out a solution for safe operations of two (or more) co-located, highly-automated satellite constellations. Such a solution has been designed and constructed, including the required ground node; and it will be exercised as a dedicated, in-flight safety experiment between the two constellations from January to September 2024. Lessons learned from this experiment are expected to feed the design of the US Department of Commerce's Tracking Control System for Space (TraCSS) space traffic coordination solution.

1. CONJUNCTION ASSESSMENT AND "AUTONOMOUS" SATELLITE CONTROL

In satellite conjunction assessment, there are a number of different risk assessment and mitigation scenarios that arise based on the nature of the two space objects that are involved. In nearly all CA operations, the protected asset, usually called the primary object, is an active payload that can make trajectory changes to modify its orbit (for orbital maintenance, safety, mission objectives, or other reasons); but the other space object in a conjunction, called the secondary object, can be of any object type, with associated ancillary consequences as follows:

- If the secondary is an inert object, such as a dead payload, rocket body, or piece of debris, then CA operations for the conjunction are straightforward: collision risk for the conjunction is assessed; and if the risk exceeds a predetermined threshold, then a trajectory change for the primary object is planned and executed in order to mitigate the collision risk for the main conjunction and at the same time not create any fresh high-risk conjunctions with other space objects.
- If the secondary is an active payload but one that cannot change its trajectory for purposes of mitigating the conjunction (*i.e.,* it lacks a propulsion system or a sufficient differential drag capability), then one proceeds with essentially the same approach as that used for an inert secondary, with the addition of notifying the secondary owner/operator (O/O) of the situation and any mitigation actions taken. The purpose of this notification is to alert the secondary O/O of the possible collision and, additionally, to communicate the burden that such secondaries impose upon actively-maintained primaries.
- If the secondary is also an object that can modify its trajectory, unless a pre-arranged concept of operations (CONOPS) exists between the two O/Os for assigning mitigation responsibility for conjunctions between their satellites, active coordination is required to ensure that both satellites not simultaneously pursue a course of action that, taken together, create an even more strongly unsafe situation. Because of latencies in the present system of submitting O/O predicted ephemerides (which contain planned maneuvers) for CA screening, without explicit coordination each O/O could select a maneuver that causes them to maneuver into each other. While such an outcome may seem far-fetched, in fact a scenario very similar to this led to the Iridium-COSMOS collision in 2009 [1]—one of the largest space-debris-producing events to date.

> However, despite this substantial lesson, O/O coordination for conjunctions between active payloads is largely to entirely unregularized: there is no requirement to register one's payload and contact information with a screening authority; there are no standardized risk levels or norms of behavior to guide O/O response to conjunctions of this type; there is no established machine-to-machine standard for exchanging conjunction-related information and decisions; and the high latency of current screening solutions often requires some amount of guesswork regarding another O/O's intentions, which frequently forces a human-enabled rather than automated solution.

To the already challenging CA situation between active payloads are now added individual satellites or constellations that perform autonomous flight dynamics. The term "autonomous" has been used broadly to describe the flight dynamics approach employed by certain spacecraft, but more subtlety in the description is required because this particular nomenclature can be both incomplete and misleading. To date, the term "autonomous" when applied to satellite flight dynamics is taken to mean that the maneuver planning calculations, decisions, and execution all take place aboard the space vehicle itself, without considering the essential contextual issue of whether supporting data for those decisions, as well as information about the particular decisions executed, are regularly available to the spacecraft. After all, if communications between a satellite and its ground node (and therefore presumably communications between the ground node and other O/Os, the screening authority, etc.) are regularly available, especially as in the limit when such communications move to essentially real-time, then it does not matter whether flight dynamics calculations are performed on the space vehicle itself or at a ground node: any information needed by or available from one is also essentially immediately available to the other. So, the meaningful distinction between traditional flight dynamics (usually performed on the ground) and "autonomous" flight dynamics (usually performed on board the satellite) depends on whether supporting data and decision information can be quickly and freely shared with other O/Os and screening authorities as part of the autonomous maneuver planning and execution process.

The Starlink system is within the industry generally labeled an autonomously-controlled constellation because of the degree to which decision-making is performed indigenously on the spacecraft. Given this legacy, autonomous flight dynamics has meant these specific things for different parts of a Starlink satellite's life cycle:

- Starlink satellites are injected from launch into a low orbit and, after a suitable health and status examination, ascend to either a parking orbit near 350 km to rephase right ascension or to their operational altitude. For these ascents, a master trajectory is developed and uploaded to each satellite to take it to its desired on-orbit location; the satellite itself plans and executes the flight dynamics to follow this trajectory. The satellite's on-board position, navigation, and timing (PNT) capability is regularly updating the satellite's current and predicted states; when the actual satellite position deviates from the master trajectory beyond set tolerances, maneuvers are planned and executed to return the satellite to its master trajectory. Satellite states are regularly downlinked to the ground system; and this ground system produces predicted ephemerides that model the satellite's expected attempt to follow the master trajectory, with covariances that indicate the degree of deviation from this trajectory that the flight dynamics system has permitted. At the end of its operational lifetime, a similar procedure is used to deorbit a vintage Starlink to an extremely low orbit, at which point a tumble is initiated to improve reentry prediction capability. In all cases, maneuvers used for orbit raising or deorbit are included in the operational ephemerides that are uploaded to Space-Track.org for CA screening.
- Once on-orbit, Starlink satellites need to maintain a specific relative position with respect to the rest of the satellites in the constellation. This is accomplished by assigning each satellite a relatively small station-keeping box, based on orbital parameters, that it needs to stay within. The flight dynamics system uses its regular state updates to determine when the satellite will violate, or has violated, its control-box boundaries, and in such cases develops and commands a maneuver to restore conformity. As the Starlink constellation has matured, these control-box sizes have been tightened; therefore, small maneuvers to maintain a satellite's needed positioning are far more frequent—often daily. Much like orbit raising / deorbit maneuvers, station-keeping maneuvers are screened by the screening authority using predicted operational ephemerides.
- To ensure the safety of the maneuvers discussed above, as well as the general safety of the satellite's future expected trajectory, the on-board flight dynamics system performs conjunction assessment on this expected trajectory nearly continuously. Because low-latency communication with the screening provider and/or other operators was not available at the constellation's initiation, a clever stratagem was developed to allow

> safe autonomous operations. The US Space Force's 19th Space Defense Squadron (19 SDS) executes conjunction assessment screenings between O/O-submitted ephemerides and the rest of the space catalogue every eight hours, and the results of these screenings are forward to the O/O as Conjunction Data Messages (CDMs). The screenings themselves are conducted volumetrically, in the sense that a fixed volume is defined about the primary object and then "flown" along this object's expected trajectory; any other objects that impinge on this volume during this simulated flight are considered possible conjunctions and result in the creation of a CDM, which gives the two objects' predicted states and covariances at the time of closest approach (TCA). If this geometric volume is made rather large, then a large number of CDMs is generated, so the O/O essentially receives a snapshot of the space catalogue in the vicinity of the satellite's predicted orbit. This means that the O/O has state and covariance information not just on objects that will pass very close to the intended orbit but also on those that could present safety problems even after executing somewhat large spacecraft maneuvers. With this information, the on-board flight dynamics software can compare its anticipated trajectory, for either Keplerian flight or with maneuvers introduced, with the secondary objects' information in the CDMs and introduce new maneuvers or modify existing planned ones in order to ensure that collision risk remains below a given threshold.
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> The above approach is implemented in the following specific way. Approximately every ten minutes, the on-board flight dynamics system recomputes a solution for its present and predicted position and, looking 48 hours into the future, assesses the adequacy of its current trajectory to meet master trajectory or on-orbit control box constraints. If these criteria will not be met, one or more maneuvers are planned to meet them efficiently; either this maneuver-altered trajectory (if one were in fact needed) or the current Keplerian trajectory is examined against the uploaded CDM information. The trajectory planning part of the system is allowed to modify the maneuver plan for any time greater than 12 hours in the future (3 hours for satellites undergoing ascent or descent). Within 12 (or 3) hours, the maneuver plan is "locked in" so that only the collision avoidance planning part of the system is allowed to make modifications. If any high-risk conjunctions are discovered, the trajectory is modified and reassessed until one is identified that meets flight safety standards, and the details of this trajectory (*i.e.*, initial state and maneuver plans) are downlinked at the next reasonable opportunity. Typically, planned maneuvers take place within about five hours of the maneuver plan's finalization for on-station satellites, and within about an hour for satellites undergoing ascent or descent. In some cases, executed maneuvers will end up causing safety issues further in the future than the twelve-hour event horizon that the flight dynamics software considers. The necessity of a follow-on maneuver in these situations is simply accepted.

How well does the Starlink approach work to secure safety from collisions? For inert secondaries, the situation is essentially as straightforward as it is for an O/O conducting flight dynamics in the traditional manner from a ground station: most predictions of future states for inert spacecraft are stable; so with the use of conservative, risk-averse thresholds for high-risk conjunction identification and mitigation, the screening information provided to the spacecraft, despite the data latencies, is adequate. For secondary objects that are typical active payloads (that is, not highly automated in their flight dynamics), the situation is manageable; but a prevenient, somewhat detailed agreement between the two parties is needed. A rubric must be established, well in advance of any actual conjunctions, that dictates which of the two parties will take mitigation action under which circumstances. The maneuver-responsible party will, of course, actually take the maneuver actions, ensuring that they mitigate the collision risk adequately. The non-maneuvering party, for its part, will need to agree to continue to follow its advertised trajectory until TCA has passed in order to ensure that the maneuvering party has based its safety calculations on a trajectory for the secondary that will actually be followed. This is in fact the arrangement that SpaceX and NASA have established by Space Act Agreement to ensure safety from collision between their two fleets: SpaceX will take responsibility for all needed CA risk mitigation actions, and NASA will ensure that its satellites express all intended maneuvers (through shared ephemerides) at least 24 hours ahead of maneuver time and not change that planned trajectory, allowing sufficient time for the standard screening process to complete. This arrangement has the drawbacks of making one entity responsible for all the maneuvers and imposing trajectory change restrictions on the other, but on the whole the approach has proven effective and workable.

However, for cases in which both objects belong to autonomously-controlled constellations with short event horizons (which both are likely to have, as short turn-around time is one of the main advantages made possible by highly-automated flight dynamics), the situation is simply not resolvable. When a conjunction arises between spacecraft from two such constellations, neither is able to inform the other expeditiously about near-term maneuver plans, so there is no way for one constellation to know the intentions of the other. As such, both satellites in the conjunction may plan CA risk mitigation maneuvers (RMMs) and, in addition to unnecessary maneuvering, could well create a situation in which both satellites maneuver into each other. Even if there is an agreement that one of the two constellations will take responsibility for CA mitigation actions, if the two constellations have similar event horizons, one might be planning a general station-keeping maneuver at the same time the other is planning a CA RMM, again creating a situation in which the satellites maneuver into each other. Additionally, completely obligating one party to be responsible for all CA mitigation actions is unlikely to scale with the deployment of multiple large-scale autonomously maneuvering constellations. There has been awareness of this challenge for some time; but because there have not been two collocated constellations with automated, short-event-horizon CA capabilities, the community has lacked a forcing function to develop a resolution.

2. THE “STARLING” CONSTELLATION AND NEED FOR AN AUTONOMOUS CA SOLUTION

Oscar Wilde once remarked that “life imitates art far more than art imitates life,” and one finds an instantiation of his thesis in the advent of the NASA Starling effort: a four-satellite constellation (or “swarm” in NASA parlance) funded by the Small Spacecraft Technology Program within NASA’s Space Technology Mission Directorate (STMD) to demonstrate satellite autonomous operations, flight dynamics, and control, including automated constellation reconfiguration. In addition to its name differing from “Starlink” by a single letter and having the same largely autonomous flight dynamics paradigm, the ride-share that Starling obtained was slated originally to deliver the constellation to a 550km circular orbit—directly in the midst of the Starlink constellation. While follow-on negotiations with the launch provider succeeded in raising the injection altitude somewhat, the Starling constellation as delivered does present satellite conjunctions, although typically those below the usual thresholds of action for CA mitigation, to one of the Starlink constellation’s shells. The needed forcing function was thus provided to work out the CONOPS for, and implement in prototype, a solution to the problem of CA for collocated constellations using highly-automated flight dynamics.

To accomplish this, a consortium was formed among the following participants and actors:

- NASA Ames, the implementing entity for the Starling system and for the Federated Airspace Management Framework, or “Freddie,” drone deconfliction architecture, which is being leveraged for the present experiment;
- Emergent Space Technologies (recently acquired by York Space Systems), the supplier of the Starling satellites’ autonomous flight dynamics software and the support contractor for the modification of “Freddie” for orbital operations;
- SpaceX, the developer and operator of the Starlink constellation;
- NASA Headquarters’ Conjunction Assessment Program Officer (CAPO) and CA Chief Engineer, who oversee CA for the Agency and are serving as the chief technical authority (CTA) for this experiment ;
- NASA Conjunction Assessment Risk Analysis (CARA) program who provide CA subject matter expertise; and
- Department of Commerce (DOC) Office of Space Commerce, who provided modest financial support and participated in the effort in an observer status.

The Consortium’s purpose was to develop the needed CONOPS for the safe operation, from a CA perspective, of two or more autonomously-operated, collocated constellations. Active work on this problem began in the summer of 2021, with NASA Ames creating and funding a mission extension to the original Starling mission—Starling 1.5—whose purpose was to support CONOPS development as well as build out prototype infrastructure for the ground node. The onboard autonomous maneuvering software for the original Starling mission, consisting of Emergent’s Navigator and Autopilot products, has the capability to perform on-board Pc calculation and mitigation for vehicles operating in proximity that are sharing state and covariance information. This system was extended to include an external catalog, populated with predicted states, covariances, and times of closest approach using the same CDM-based method utilized by Starlink as described above, and autonomously managed and integrated with Autopilot using Emergent’s Commander autonomy engine. Once an approach was developed and tested, with SpaceX making any necessary modifications to their operational system, the Starling system would, at the end of their 1.0 mission, transition to Starling 1.5, at which point an actual live experiment with the new paradigm would begin: the threshold for actionability for conjunctions between Starlink and Starling would be artificially lowered to a level well below the usual mitigation action level of 1E-04/05, and the new paradigm would be exercised for approximately a nine-month period, with both human monitoring (with kill switches) of the automated CONOPS/system and substantial data collection so that the CONOPS and implementation can be fully understood and tweaked/improved if necessary. The altitude of the Starling constellation can be adjusted in order to create the desirable number of conjunctions, and any serious conjunctions (above the 1E-04/05 level) will be worked manually, outside of the new CONOPS, in order to ensure safety during the experimental period. The results of this experiment will inform the DOC's development of their Tracking Control System for Space (TraCSS) orbital safety system, currently also in development. At present, the Starling 1.5 experimental period is scheduled to begin in January 2024 and run for nine months.

3. AUTONOMOUS CA CONOPS AND ARCHITECTURE: HIGH-LEVEL CONSIDERATIONS

The outline of the approach to the Starling 1.5 autonomous CA experiment was given above, but of course it is necessary actually to develop a proposed CONOPS and realize it in software so that the experiment can actually be conducted. The drivers for producing the data for the CONOPS and its architectural implementation are given below.

First, a capability is needed for O/Os to have their predicted ephemerides screened against each other in an extremely low-latency manner in order to accommodate the short event horizons that autonomous satellite systems will use. This means, of course, that such systems will simply have to be able to share their trajectory intentions reasonably expeditiously; there does not seem to be a workable system to perform trajectory deconfliction without this kind of information exchange, and the least ambiguous way to perform it is through the exchange of ephemerides. One can imagine a completely bilateral, federated system in which all O/Os distribute their predicted ephemerides to all other O/Os, with each performing the screening task separately (and repetitively) of its ephemerides against those for everyone else; but it makes sense here instead to have a single screening node to receive all the ephemerides and perform the screenings centrally, distributing the resulting CDMs to the affected parties. This repository can also contain the current intended trajectory for all of the participating O/Os' spacecraft, although there are some subtleties to this that will be discussed in the next section, in which the CONOPS for the centralized screening node is explained in detail.

Second, a structure is needed for the taking of responsibility for individual conjunctions that the screening authority identifies. There are a number of different ways that this could be approached, spanning from a centrally-managed assignment of mitigation responsibility (including dictated timelines) to the mere providing of a message board of sorts to allow O/Os to work out between themselves how this responsibility will be assigned in any given circumstance. A number of different approaches to this problem were explored, and in fact the selected solution was modified substantially as the consortium's thinking developed. In the end, a utility similar to a management aid for O/Os to take responsibility voluntarily for conjunction mitigation emerged as the desirable solution, both for the current experiment and as a CONOPS that could be extended to a large number of autonomous constellations from multiple host countries. Again, the details of the proposed CONOPS and architecture for this function will be explained in the next section.

4. DETAILED CONOPS AND ARCHITECTURE

A ground-based screening node has been designed and developed for the experiment rapidly to identify conjunctions and send conjunction screening information to O/Os, as well as maintain a set of current planned trajectories for the participating constellations. Its particular features and design parameters include the following:

1. The screening node maintains a database of the latest predicted ephemerides from all participating O/Os. These ephemerides include planned trajectory modifications and represent a precision propagation of the satellite's Keplerian orbit for non-thrusting periods.
2. Whenever a new O/O ephemeris submission is forwarded, that submission is screened against all of the other current O/O ephemerides in the screening node's database. Results that meet reporting criteria are sent as Conjunction Data Messages (CDMs) to the two O/Os involved in each conjunction. The screening node is designed to keep screening latencies to less than one minute between the receipt of a new ephemeris and the dispatch of the CDMs that resulted from the screening of that ephemeris. Because the

CA screening process is easily parallelizable, the achievement of this level of screening performance is not expected to be difficult.

3. An O/O ephemeris can be submitted for screening with any of three disposition instructions:
    a. Candidate. The submitted ephemeris is exploratory in nature and is not necessarily intended as a trajectory to be implemented by the spacecraft. Examples could include station-keeping maneuvers that might be chosen, different CA mitigation action maneuvers that might be executed, or "flight-of-fancy" trajectory changes that the O/O simply wishes to explore. Ephemerides submitted as candidates will return CDMs only to the submitting O/O and not to any O/Os that occur as secondary objects in the CDMs, for it is not clear that the O/O will actually execute the submitted trajectory.
    b. Candidate-Definitive. The submitted ephemeris is intended to become the O/O's new trajectory if it sustains the screening process without any conjunctions that exceed a CA risk tolerance that the O/O specifies. If the ephemeris sustains the screening in this way, the submitted ephemeris becomes the screening authority's current predicted ephemeris for this O/O; CDMs are still produced and forwarded to all relevant O/O parties for situational awareness and potentially for the use by other O/Os, since there may be conjunctions that are not considered high-risk for the submitting O/O but might meet that designation for other O/Os. If the ephemeris does not sustain the screening, namely that the screening produces at least one conjunction that exceeds the risk threshold that the submitting O/O has selected, then the submitted ephemeris is not embraced as the O/O's current trajectory, the screening authority's ephemeris database is not updated with this ephemeris, and the resulting CDMs are sent only to the submitting O/O (to aid in an expected replanning effort). This paradigm can also easily accommodate the submitting of a ranked set of proposed ephemerides; in such a case, the system will accept the highest-ranked ephemeris in the group that sustains a screening action without producing any high-risk conjunctions, returning to the O/Os CDMs for only that particular ephemeris.
    c. Definitive. The submitted ephemeris is the ephemeris that the O/O currently intends to follow, regardless of the high-risk conjunctions that it may present; and the screening authority will thus update its database with this ephemeris and distribute CDMs appropriately, one or more of which might indicate a high-risk conjunction. If this latter case inheres, a high-risk conjunction will be flagged and handled by mitigation action assignment procedures (to be described presently).

The above definitions are summarized in Table 1 below:

Table 1: Ephemeris Screening Instruction Possibilities

Title	Explication	Commentary
Candidate	This is a trajectory I am exploring	• Exploratory maneuver planning, for either RMMs or orbit maintenance maneuvers • Any other situation in which screening results, without accompanying actions, are desired
Candidate Definitive	This is a trajectory, or ranked set of trajectories, I will use if one of them yields a clean screening	• O/Os who want simplicity of less-iterative CA and are willing perhaps to take on more of a maneuver burden to achieve that • O/Os with high(er)-latency ground comm and therefore cannot sustain protracted iteration
Definitive	This is my current intended trajectory	• Non-maneuverable payloads • O/Os who do not intend to cooperate with orbital safety • O/Os who wish to manage CA responsibility directly with other O/Os, allowing informal agreements; can work well if O/O has low-latency ground comm

It would seem, and indeed to the CONOPS developers for some time it did seem, that the candidate-definitive category would be the appropriate *modus operandi* for everyone: the screening authority's database of current trajectories would always be "clean" because it would be populated only with ephemerides that had produced clean screenings, with no high-risk events identified; and O/Os who wished to change their trajectories would be able to use only trajectories that could achieve a clean screening of this type. On further reflection, however, some of the advantages to this method were found to be illusory, and additional problems were discovered:

- Despite the attempts to keep the screening authority's trajectory database "clean" and free of ephemerides that produce high-risk conjunctions, that is unlikely actually to be an achievable goal. First, if non-maneuverable O/Os (or, for that matter, inert objects themselves) are integrated into this construct, then natural orbit developments will create conditions in which high-risk conjunctions involving mitigation-capable O/Os will simply appear in the database. After all, one cannot reject the trajectory inputs for non-maneuverable objects (this is one of the uses of the "definitive" ephemeris submission category described above) because they will cause conjunctions with the trajectories for actively-managed satellites; and, at least some of the time, accepting ephemerides from non-maneuverable O/Os will suddenly introduce a high-risk conjunction with a "clean" O/O ephemeris that earlier sustained screening successfully. Additionally, heightened space weather activity will cause satellite predicted positions in LEO to become more erratic and subject to large changes. Under such conditions, routine O/O ephemeris updates, even when they contain no planned maneuvers, will fail the initial screenings perhaps frequently, placing an arbitrary maneuver burden on whichever of the two O/Os happens to submit the next ephemeris update. To be sure, one could draw a distinction between ephemerides for non-maneuverable objects, which must simply be accepted as submitted; and those for maneuverable objects, which in principle could be designed to be "clean" from a screening perspective at the time of submission. However, the point is that ephemerides that are clean when submitted can become unclean either by other submissions from non-maneuverable satellites or through innocuous updates to take account of propagation volatility; so one cannot presume that a submitted trajectory will remain acceptable even if it satisfies acceptance criteria at submission.
- This somewhat arbitrary placement of maneuver burden is the natural result of a first-in-first-out (FIFO) methodology for attempting to create and preserve a "clean" ephemeris database, free of any high-risk conjunctions. FIFO is a nicely transparent and formally fair construct—attributes that are important in demonstrating to a potentially large and disparate group of users the equitable nature of the approach; but at the same time, it creates suboptimal results and undercuts a sense of its own justice through its ability to be gamed. In general, it penalizes frequent updates of one's O/O ephemerides, since it is the process of resubmission that identifies conjunctions and implicitly places the mitigation burden on the resubmitter. The screening node could try to mitigate this effect by requiring ephemeris updates at some regular cadence (this prevents an O/O from submitting less frequently in order to try to push mitigation actions to others), but this approach would only accentuate the arbitrary distribution of the mitigation burden, as small (potentially very small) differences in submission times would ultimately govern the apportionment of mitigation responsibility. But the entire arrangement, with or without attempted corrections, cuts against optimality because for any particular conjunction, the astrodynamics conjunction geometry and the O/Os' particular priorities are what actually determine the preferred assignment of mitigation responsibility.
- In principle, the screening node could contain somewhat elaborate information about each payload and a substantial ruleset that would allow it to assign mitigation responsibility in a more optimal way; instead of just rejecting a submission that introduces a problematic conjunction, the ruleset would engage and perhaps reject instead a previously-accepted ephemeris, sending to the O/O the relevant CDMs and a notification to plan a mitigation action. This would, however, require the development of a capability to make mitigation decisions for all pairs of O/Os, necessitating the willingness of all O/Os to disclose internal (and perhaps proprietary) details about their constellation and to accept a formalized decision logic that the screening node could implement. This level of disclosure and submission to a centralized decision authority would be very difficult to arrange even within a single service area (*e.g.*, US, EUSST); and in the current and projected future space environments, it cannot be seen as a live possibility for international space traffic coordination/management (STC/STM). Furthermore, a centralized authority would not easily accommodate bilateral arrangements between O/Os. O/Os who expect their constellation of satellites to have regular and persistent conjunction issues with another constellation, such as the current experience between SpaceX and OneWeb regarding the ascents and descents of OneWeb satellites through the Starlink constellation, can work out particular methods for assigning mitigation responsibility that are proper to their specific situations. To administer such arrangements through the screening authority, that central authority would need to possess the infrastructure necessary to administer an essentially unbounded ruleset

that might change regularly and, worse, could be dependent on transient constellation conditions about which the screening authority would not have immediate knowledge.

For the above reasons, the required use of the Candidate-Definitive submission designation was determined by the Consortium to be tenaciously problematic; it therefore prompted a rethinking of the entire presumed paradigm for facilitating the assignment of conjunction mitigation responsibility. After considerable reflection and reworking, what emerged was a methodology that still employed a centralized screening authority but allowed O/Os of all types to choose freely among the three submission paradigms, including the use of the "definitive" designation by O/Os who are both capable of and disposed to mitigation. Instead of rejecting ephemerides that create high-risk conjunctions, the screening authority will inform the O/Os of the conjunction, forward the appropriate CDMs to both O/Os, and create an entry on the screening authority's "conjunction of concern" board that will allow the O/Os to indicate their posture towards this particular conjunction, choosing among one of three options:

1. None. Neither O/O has claimed or refused responsibility for this conjunction. "None" is the default state in which all identified conjunctions of concern begin, and it indicates that neither O/O has yet taken a position. This actually provides useful information in that it communicates that the other O/O has not made any definitive plans to effect a mitigation; so if an O/O feels that the risk has become great and there is little time left before a decision is required, that O/O can go ahead and claim responsibility for the mitigation.
2. Claimed. An O/O has claimed responsibility for mitigating the conjunction, and a new ephemeris will be submitted shortly that will both mitigate the conjunction adequately and will not introduce any fresh conjunctions that exceed that O/O's standard Pc mitigation level. The non-claiming O/O should presume the conjunction will be mitigated and should attempt to refrain from introducing any fresh trajectory changes between the present time and the conjunction's TCA; or at the least the non-claiming O/O should recognize that doing so may subject him to having to make his own subsequent mitigation maneuver if this new trajectory causes difficulties with the original mitigation action that the claiming O/O implements. When the claiming O/O submits a new ephemeris that, based on its screening results, mitigates the main conjunction and does not introduce fresh conjunctions of concern, the conjunction will be grayed out on the screening node's conjunction board but will remain there as a visible entry (indicating the disposition result) until the TCA has passed. If space weather or other natural perturbations causes trajectories to deviate and risk to increase, the conjunction will again be marked as requiring action.
3. Refused. The responding O/O has refused responsibility for this conjunction. Such a response seems *prima facie* defiant, but there are a number of reasons that this response might be given in an overall constructive environment:
    a. The satellite inherently lacks the ability to modify its trajectory significantly enough to mitigate the conjunction—what would commonly be called a "non-maneuverable" satellite.
    b. The particular satellite in question lacks the ability to modify its trajectory significantly in this case, due to hardware/software/communications failure; this could be either a temporary or permanent outage for this spacecraft.
    c. The conjunction might appear for the first time after the satellite's event horizon for that TCA has closed, meaning that insufficient time before TCA remains for the O/O to plan and execute a maneuver safely.
    d. The conjunction might not violate an O/O's safety posture, meaning the Pc is not high enough that the O/O feels compelled to pursue a mitigation action. It is to be hoped, of course, that a standard risk tolerance level could be established that all O/Os would at the least embrace (a Pc of 1E-04 is currently used by a large percentage of O/Os and thus could be considered to be such a standard); but some O/Os may wish to take a more conservative posture, and conjunctions that violate the mitigation threshold of either O/O will appear on the "Conjunction of Concern" list.
    e. The O/O may be furnishing their ephemerides as a courtesy to the orbital safety "region" overseen by a particular screening node but not intend to participate in any mitigation actions; one can imagine certain O/Os holding a position of this type. A standing "refused" response for such O/Os makes clear to all participants who will need to take action to resolve any serious conjunctions.

The three O/O response types are summarized in Table 2 below:

Table 2: O/O Conjunction Response Possibilities

Response	Explication	Commentary
None	Neither O/O has taken a position on this conjunction	• May be well in advance of either O/O's mitigation action commitment point • Negotiations between the two O/Os may be taking place presently
Claimed	One of the two O/Os has claimed responsibility	• This could be as a result of general guidance, a bilateral arrangement between the two O/Os, or for an O/O's expedience
Refused	One of the two O/Os has refused responsibility	• The refusing O/O may not be maneuverable or be experiencing an anomaly • The conjunction may first appear after the O/O's mitigation action commitment point • The refusing O/O may not participate in the particular screening provider's orbital safety program

An arrangement of this type, in which the O/Os voluntarily take responsibility for conjunctions, feels underwhelming at first—as an abdication of an opportunity to provide true, uniform space traffic coordination/management. However, once considered in more depth, the following advantages emerge:

1. <u>Bilateral arrangements are easily accommodated</u>. Of principal importance to an STC/STM paradigm is not so much which satellite in a conjunction of concern performs a mitigation action but rather that in such situations a mitigation action by at least one of the satellites is in fact executed. While a standard ruleset could be developed and enforced by a central authority, such a paradigm would make bilateral arrangements between constellation operators difficult: the mitigation apportionment logic would have to be spelled out in complete detail and implemented by the central authority, and appropriately modified every time a bilateral arrangement was tweaked. There are also expected to be situations in which temporary arrangements between constellations arise, or mitigation responsibility meted out in daily meetings during intense periods, such as waves of ascent of large numbers of satellites through a constellation. Allowing constellations the flexibility to manage situations of this type with bilaterally-tailored rulesets that could be changed frequently is an important consideration. To be sure, certain basic rules, such as not permitting conjunctions with Pc values greater than a universally-accepted standard (such as 1E-04) to persist, would need to be honored; but the particular entities performing the mitigations to honor such rules need not be specified directly by the management authority so long as these mitigations take place in a manner acceptable to the participating O/Os.
2. <u>Compliance is enforced by audit rather than active management</u>. It is presently the case even for constellations licensed in the United States that different rulesets for orbital safety and debris mitigation are applied to different constellations, and it is certainly imagined that the rulesets will differ even more broadly across licensing nations or international entities. Given that global STM/STC is likely to rely on a collection of federated systems rather than be administered by a single international authority, it is unlikely that satellites from different nations, or different federated collections of nations, will all submit to a single authority to adjudicate STM/STC situations and make direct mitigation assignments. However, what is both far more appealing and likely to be effective in a federated environment is instead to make the history of conjunctions of concern, and the O/Os' response to these conjunctions, available for audit by the constellations' licensing agencies. These agencies can examine how mitigation responsibility was actually apportioned and determine whether the constellations under their authority are confirming to the requirements of their license, and if not, they can take appropriate remedial action within their own domain. Such audits need not be concerned about mitigation apportionment *per se*, so long as mitigation actions occur when required and all participants in those conjunctions are themselves satisfied with the apportionment that was realized. O/Os can complain to other constellations' licensing authorities should they believe that a constellation is not following accepted best practices. This approach may appear as a "passive-aggressive" STM/STC approach, but the centralized alternative did not actually have any direct authority either: there was really nothing the centralized authority could do if an O/O simply refused to

implement a STM order. With the present approach, it is at least obvious when an O/O is not taking responsibility for a conjunction of concern (through a persistent “none” or an actively-logged “refused” status), and the other O/O can thus take the mitigation action, ensuring safety, and lodge a complaint *ex post facto*.

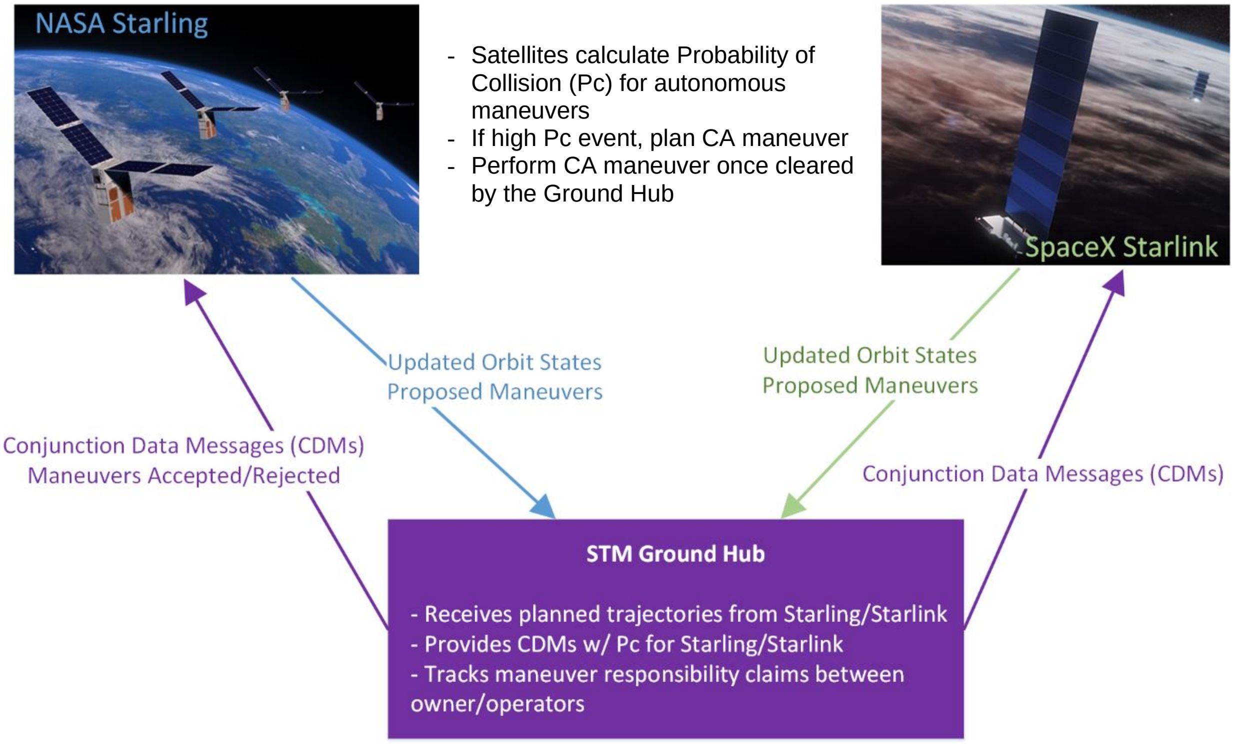
3. <u>The construct is robust against communications or O/O outages and problems</u>. Expanding the thinking of item 2) above, there was always a concern that a mitigation action directed by a central authority might, for unintentional reasons, not be honored. Communications outages or downtime at the O/Os ground station or flight dynamics facility could result in a mitigation order not being received at all or not being supported by a functioning O/O ground station. The voluntary apportionment paradigm will eliminate at least some of these possible miscarriages by requiring the active, closed-loop taking of responsibility for mitigation actions; and if a ground node does go down, the switching of the O/O’s mitigation posture to “refused” will in many cases allow the other O/O to plan their own mitigation action to cover for this outage and preserve safety.

To be sure, the advent of the voluntary apportionment construct does not eliminate many of the subtleties and difficulties that must be confronted in order to assemble a workable paradigm. For example, timeline mismatches between different O/Os create situations in which a conjunction’s mitigation commitment point might be at 24 hours to TCA for one of the O/O’s in a conjunction of concern but not be reached for the other O/O until 12 hours; by simply waiting, in principle the O/O with the shorter event horizon could always avoid mitigation actions between these two O/Os. Issues of this type cannot be avoided under any paradigm, and it will be necessary for the licensing authorities to develop and promulgate guidance to ensure equitable distribution of mitigation responsibilities. But at the least, the present approach allows for the direct embrace and implementation of such guidance by O/Os, with the implementation verifiable by audit.

5. EXPERIMENT CURRENT STATUS

Graphically, the high-level view of the experiment set-up is given in Fig. 1 below:

Fig. 1: High-level diagram of experiment structure and data flow



Once the experiment CONOPS was fleshed out (as described in the previous section), it was necessary to stand up and develop the needed software (both ground- and space-based) at the two O/O locations (Starlink and Starling), as well as the central ground hub, which serves as the screening authority. For the former, both O/Os had to create automated constructs to generate ephemerides that include planned maneuvers and, before maneuver execution, submit them to the screening authority and receive and process screening results. For the latter, the low-latency screening and conjunction management utility had to be built out. NASA Ames was given the lead on creating the architecture, for which they drew upon their Federated Airspace Management Framework, called "Freddie", which was developed for federated drone deconfliction. A structure diagram of the ground node is given in Fig. 2 below:

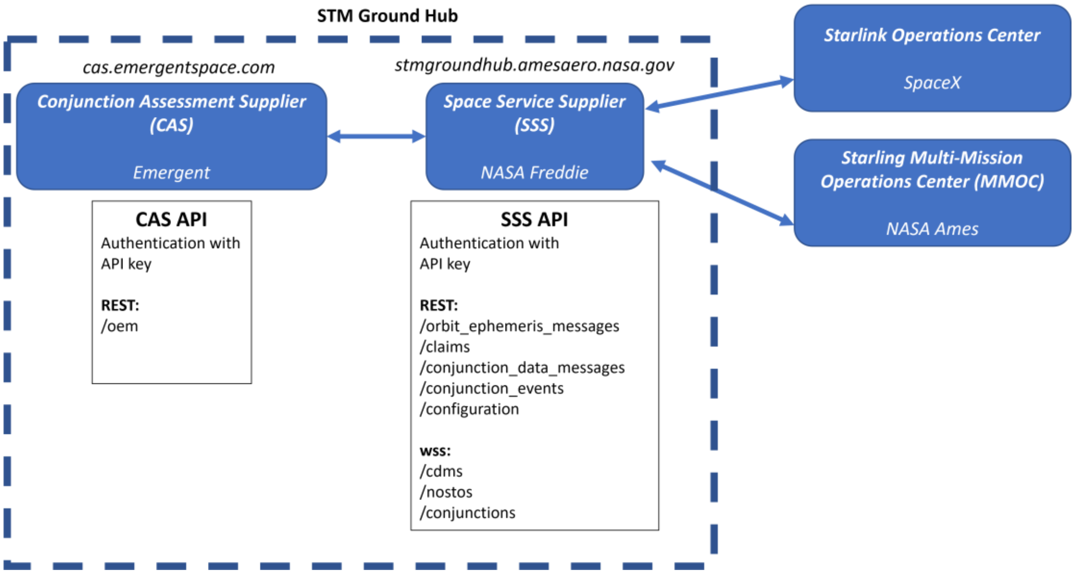


Fig. 2: Structure diagram of Freddie architecture as applied to Starlink/Starling experiment

One can see here the supervening structure within Freddie, giving API links to all the major functions; these include submitting ephemeris messages, the "board" of conjunctions of concern, the O/O response to those conjunctions at any point, and the distributions of CDMs and Notices to Space Operators (NOTSOs). The actual CA screening algorithm is modularly separated, allowing the easy swapping-out of this capability as needed or desired.

The modified Freddie architecture has been created and unit tested, and the needed O/O modifications for the Starling satellite system have been completed as well and are being validated for upload at the completion of the primary Starling mission. Starlink software modifications should be in place mid-fall 2023 to allow for final testing before the start of the formal experiment, which is presently slated to run from January to September 2024.

6. CONCLUSIONS AND FUTURE WORK

The Starling "improvident" ride-share to the midst of the Starlink constellation has presented a quite useful opportunity to create, and in 2024 to test, a new construct to perform CA between constellations that are highly automated in their maneuver paradigm. The assembled construct appears to address all the major difficulties and provide a conjunction coordination system that could be extended to a large number of (large and small) constellation operators, expediting information exchange and mitigation responsibility allocation while allowing individual bilateral agreements on conjunction handling between O/Os.

It is NASA and SpaceX's intention to hold a major public event on this CONOPS in late fall 2023, probably under the sponsorship of one of the major space industry trade associations, in which a very detailed set of presentations on all aspects of the approach are given and community discussion and feedback engendered. The degree to which such feedback can be incorporated into the experiment structure is of course not clear, given the need to freeze baselines for flight software close to the beginning of operations; but constructive suggestions will be considered and migrated into the experiment to the maximum extent possible. Additionally, it is the intent to document fully the results of the experiment in future conference papers and journal articles. The initial formulation of this CONOPS and any subsequent public comment, as well as the results from the experiment once it is run, will be considered by the Department of Commerce as inputs to the TraCSS system for deployment of a similar capability as part of this system.

7. REFERENCES

[1] Shepperd, R. and Ward, D. "A Review of the Collision between Iridium 33 and COSMOS 2251." Second International Conjunction Assessment Workshop, Paris France, June 2019.