How to Categorize an Avoidance Maneuver: Untangling the Iridium Experience

Ryan Shepperd
Iridium

Abstract

With the upcoming transition of collision screenings from the 18th/19th Space Defense Squadron to the Department of Commerce TraCCS, a review of collision assessment and avoidance performance for the last 15 years could inform these current endeavors. Transparency among operators also promotes safety for all by identifying those risks most effectively controlled. Moreover, understanding today's capabilities aids equitable rule making for licensing. With those objectives in mind, collision assessment and performance are shared through the lens of operating the Iridium® constellation at 780 km.

Key metrics examined are the number of conjunctions received, the number of alerts generated, and the related number of mitigation maneuvers. An alternative means to count the latter is discussed in light of continually improving station-keeping that opportunistically seeks to minimize collision risk. Sharing Iridium's history in these areas may aid future stewardship of the space environment for all.

1. OVERVIEW

First launched in 1997 with a vehicle beginning in refresh in 2017, the Iridium constellation was the first commercial crosslinked telecommunications constellation with global coverage. The current constellation of 80 satellites consists of 6 planes of 11 satellites each along with 14 spares. The mission orbits have a period of 6028 seconds (780 km altitude) inclined at 86.4 degrees and perigee frozen over the north pole.

The constellation has endured three solar cycles with the first peaking in 2003. The modern era of actionable collision assessment data and active collision avoidance only began in 2009, though, during solar cycle 24, whose activity was mild compared to historical cycles. The advent of a stronger cycle 25 renewed interest at Iridium in this key influence on space object tracking and, by extension, quantifying performance of collision risk mitigation. With the Office of Space Commerce set to begin providing collision screening data via TraCCS, a review of Iridium's progress may also inform as to the aspects that have affected the reduction of collision risk. In particular, the benefits of larger screening volume size and importance of understanding solar volatility will be discussed.

Companies are also beginning to be required to report conjunction events as part of their FCC licensing[4]. What might not be immediately clear is what constitutes or should constitute an event and how to formulate criteria that could be useful for comparison or trending. Three types of metrics are discussed and examined here from the perspective of the Iridium experience. The amount of conjunction data, the number of alarms, and the number of maneuvers that count as collision avoidance (COLA) maneuvers.

2. CONJUNCTION DATA VERSUS ALERTS

A principal metric of concern is often the number of conjunction alerts issued to an operator. While alerts are of paramount interest, they are sometimes confused with the number of conjunction data messages (CDMs) issued to a satellite operator. The two are not the same. The latter is data, useful for a diversity of purposes beyond just situational awareness; the former is that subset of the data exceeding a probability of collision (Pc) threshold of concern. In the case of some operators, including Iridium, an alert is also determined internally using those data independent of the screening provider by incorporating the best knowledge of projected hard body area and position of the operator's asset. Historically, the correlation between alerts issued and alerts internally assessed has been poor for maneuvering satellites, albeit improved and applicable for those alerts now based on submitted operator ephemerides.

A larger superset of alerts, on the other hand, are the data from which they are derived. The total number of CDMs available to an operator is dependent on the screening volume and predictive time span. The change in the number of conjunctions within this volume can be a direct measure of the local debris environment seen by a constellation if the volume is constant. However, the screening volume has not been constant, a caveat to remember when these numbers are reported. The volume has, in fact, grown over time per the request of operators who sought that enlargement both to decrease surprise conjunctions and to facilitate station keeping maneuver pre-screening. Today's volumes thus include far more conjunctions than just those that could be a concern and are unrelated to an assessment of false alarm rates (Fig. 1).

Unfortunately, a perception occasionally resurfaces that CDM numbers should be limited. The 18th Space Defense Squadron (SDS) at the Combined Space Operations Center (CSpOC) implemented an additional probability filter of 1e-07 on their high accuracy catalog (HAC) versus HAC screenings, partially nullifying an original point of the 95% capture volume, which is to capture all conjunctions at 7 days that could eventually be a concern. Fortunately, no such filter was placed on the operator ephemerides versus HAC screenings with the larger volume, preserving safety through situational awareness. Still, the number of CDMs continues to be inappropriately criticized, such as recently during the February, 2024, TraCCS listening session[10], when the number of alerts should be the only legitimate concern.

As an analogy for the non-operator, CDMs are akin to visibility through an automobile's windshield and mirrors. Alerts are akin to the warning lights on the mirrors of modern cars and the audible alarm if a driver activates a turn signal in the presence of an adjacent car. Few would want to drive blindfolded with only the binary warning indicator. Conjunction data messages are appropriately named as data and should not be conflated with alerts, which are the subset of those data that exceeds a probability of collision threshold.

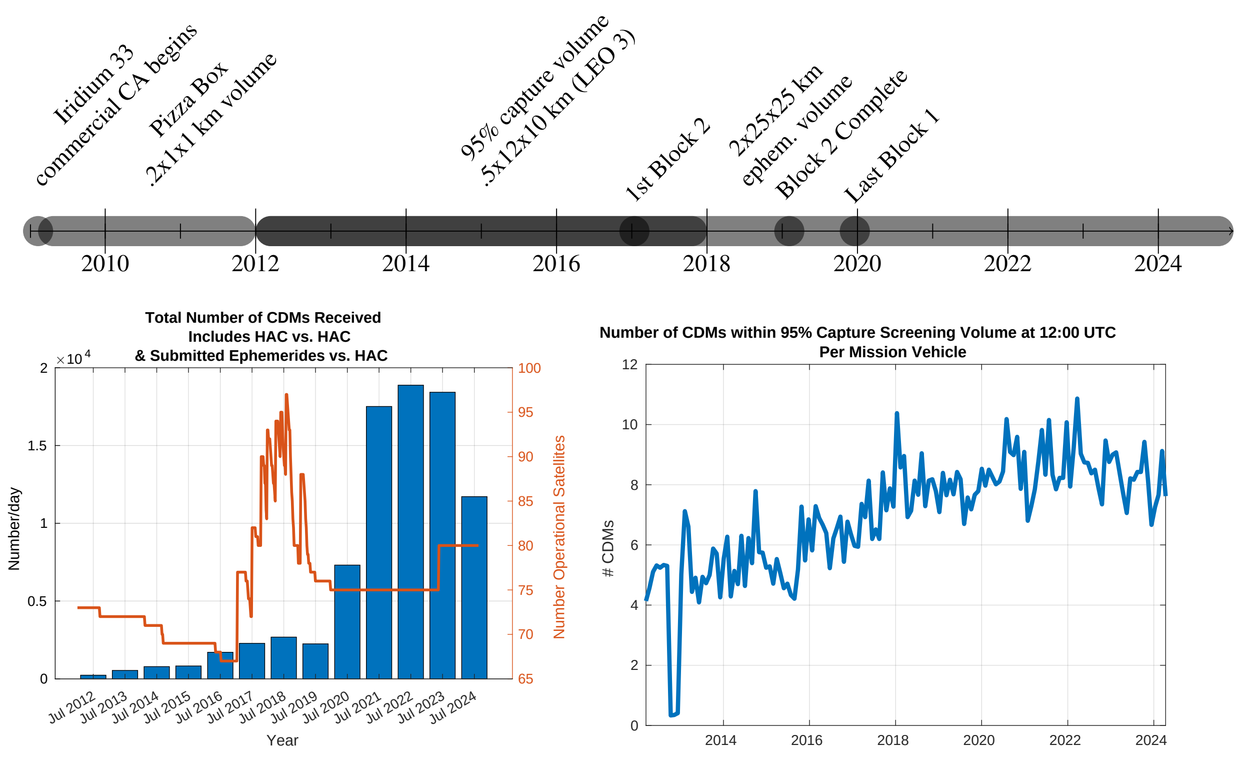

Figure 1: On the left, the total Number of CDMs received; on the right, filtered by the 95% capture volume per vehicle. After growing for several years, the normalized number has plateaued (does not include August, 2024, CZ-6A upper stage breakup) whereas the total number has increased in accordance to the operator's needs for greater usability.

3. ALERTS

While the CDM numbers in Fig. 1 are informative to track operational screening and space object population changes, CDM counts are not a good metric of risk. The number of alerts issued by the screening provider, however, would better trend risk if they used consistent criteria through time, tracked the actual position of the operational satellites, and easily indicated when the criteria was no longer met before TCA.

The alerts issued by the 18th/19th SDS meet the 1st case of consistency, but it's up to the recipient to know if new data has rescinded the alert. More detrimental, because the 18th/19th SDS does not utilize shared operator maneuvers in their orbit determination, their HAC state for the operator does not track known position well after maneuvers. Alerts based on HAC versus HAC screenings are often inaccurate. Beneficially, alerts based on HAC vs operator ephemerides are now also issued, which are useful but not comparable across operators because they depend on the covariance the operator chooses to share. The ephemerides shared by Starlink with the 18th/19th SDS and other operators on space.track.org, for example, clearly blends an orbit determination solution with radial, intrack, crosstrack limits to account for future maneuvers. Similarly, Iridium thus far shares covariance on the same platform that is known to be more conservative, as a precaution, rather than the covariance produced and used internally. Such decisions affect the comparability of alerts.

Fig. 2, on the other hand, represents Iridium's internally assessed alerts, the subset of those data that surpassed a threshold for mitigation. While still not easily comparable with other operators, it captures those events absent some of the issues discussed. It also records conjunctions of concern before externally produced alerts were even issued and is based on the operator ephemerides and hard body knowledge. Events of concern have passed through higher fidelity Pc methods and checks of data quality. The data encompasses two different satellite series of approximately the same size, but the thresholds were adjusted slightly to accommodate better capabilities of block 2. The thresholds used, in Table 1, are approximately the 1e-4 identified in the Space Safety Coalition's Best Practices for the Sustainability of Space Operations[1] and the AIAA Satellite Orbital Safety Best Practices [6] but were originally derived by the constraints of adhering to a control box and acceptable service disruptions. The thresholds were empirically chosen to perform the most COLAs, reducing the most risk, without disrupting service, given the existing debris population at the altitude of 780 km.

Worth explaining, Iridium has always used two thresholds for conjunctions: catastrophic and non-catastrophic. Originally, catastrophic caught the quintessential concern–the collision of Iridium 33 with COSMOS 2251. Recognizing the danger of not only losing a satellite but creating 2 new large debris fields, conjunctions with large objects used a lower threshold plus, in case covariance realism or hard body radius were insufficient, a safety catch of a 100-meter miss distance. Later, the categories of catastrophic and non-catastrophic adopted additional rigor by using the NASA CARA implementation of collision consequences [5][7]. Catastrophic for block 2 includes just a large breakup of the primary object regardless of the secondary size.

Herein these explanations mark a distinction in using alarms, whether self-generated, or provided externally: Collision avoidance alarms and actions are difficult to compare between operators, orbital regimes, and over time. Different operators utilize not only different probability of collision thresholds but different probability of collision methods. Though the industry has converged on a best practice of 1e-4 as a threshold, some operators such as Starlink use more conservative thresholds, and the timing threshold can be dependent on mission objectives and constraints. Further complicating a comparison, probability calculations use differing levels of conservatism and simplifying assumptions. Beyond some differences between the various 2D, 3D, and Brute Force Monte Carlo Methods available today[9], one of the most influential differences is the choice of hard body area or radius.

When state vectors agree, and the same Pc Foster method of the 18th/19th SDS is used, hard body radius explains the differences between Iridium's assessment of collision probability and that of the 18th/19th SDS included in the CDM. Iridium uses knowledge of conjunction geometry and solar array positions to compute the bounding circle for a conservative assessment of 2D and 3D Pc. When refinement is needed, Iridium uses the actual projected area in Brute Force Monte Carlo for a less conservative but truer Pc assessment. For the secondary object, known dimensions are used when the object is not debris. The 18th/19th SDS uses static default covariances for all objects by type or class. This shifting balance in model fidelity complicates trending or comparison between sources.

Additional variability affecting the alarm and action metrics in Fig. 2 is the time remaining to closest approach. Current collision assessment screenings in LEO start 7 days from TCA. Traditionally, Iridium has counted events at

72 hours before TCA as a compromise time at which many data are reliably consistent enough to be deemed actionable. However, Iridium does not always react immediately and can wait and act 1/2 orbit from TCA. As covariance naturally shrinks with additional measurements and less propagation time to TCA, the Pc falls away for some conjunctions identified at 72 hours (and grows for others). One might argue events of concern, for at least consistent trending, should be identified instead at the last actionable epoch, though such may still not share commonality among operators. To remain consistent with Iridium's past and current rule set, data analysis here uses the 72-hour running start. Any conjunction with believable data exceeding criteria between 72 hours and TCA is counted, leaving an ambiguity for the case when the conjunction later improves without action. The no-action category ideally includes those conjunctions that later improved. An early reaction, contrariwise, could mitigate conjunctions that later would not need mitigating. The events in Fig. 2 span 72 hours to TCA, and early reactions likely bias the counting. Given less propagation time from the last measurement, Pc assessed near TCA is not the same as at 72 hours.

Table 1: P_c Event Criteria for mission and spare vehicle phases, time to TCA < 72 hours

	non-catastrophic	catastrophic
Block 1	2.0×10^{-4}	1.0×10^{-4} or miss < 100 meters
Block 2	1.2×10^{-4}	6.0×10^{-5}

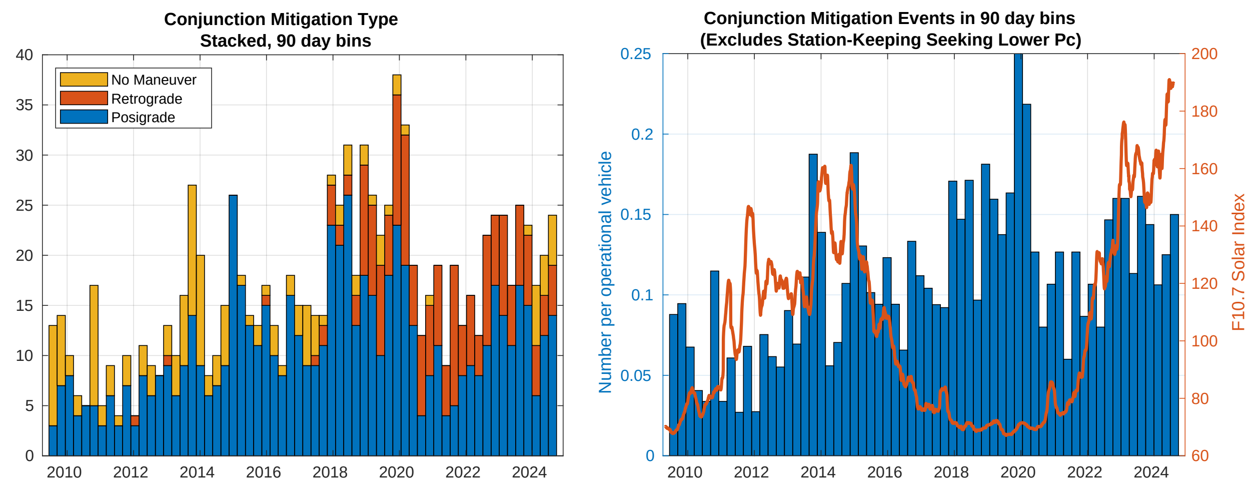

Figure 2: Internally assessed alerts. On the left are the binned counts by action; on the right, the total events have been normalized by the number of operational vehicles to account for changes in constellation size. The vehicle phases of ascent from launch injection and deboost for atmospheric reentry follow more constraining criteria based on only Mahalanobis distance and are not counted here.

4. INTERNALLY ASSESSED EVENTS AND SOLAR ACTIVITY

An interesting complexity in alarms and avoidance maneuver numbers is an approximate inverse relationship with solar activity. When solar activity is lower, the number of avoidance maneuvers has been higher; when solar activity is higher, the number of avoidance maneuvers is lower. This relationship has two contributions.

First, the opportunistic minimization of collision probability through station keeping is greater during higher solar activity with higher atmospheric density. There are more station-keeping maneuvers and more opportunities. In a lower drag environment, the period between maneuvers can be long and any concerning conjunctions in those periods must be handled with a dedicated avoidance maneuver. The atmospheric drag history of Iridium in Fig. 4 shows the affect of the two solar minimums on the rate of change in semimajor axis where the change can approach or even exceed zero to be slightly positive. All negative changes must be countered with prograde thrusting to remain within the control box but when the changes are low, the time between maneuvers is long. Fig. 5 shows that time between maneuvers did not enter the 7-day screening time span until 2023. From 2023 on, opportunistic station-keeping existed to address a concerning conjunction. Before 2023, a vehicle was more likely to need a dedicated COLA during longer pauses between maneuvers.

Second, an inconvenient truth is just because an object is reliably tracked does not mean it can be avoided. Larger covariances do not produce collision probabilities that surpass oft-chosen thresholds. The largest covariances can also surpass a typical control box size, making the object's position error impossible to avoid within mission constraints. Covariance size has a direct relationship to solar activity, or solar variability. One metric that reveals this relationship is the Pc assessed with a zero miss distance.

In Fig. 3, all the conjunctions within the screening volume are modified to have a zero miss distance and the Pc is calculated. Those conjunctions resulting with a Pc above the threshold of interest are said to be actionable. If the miss distance really were small, they would be a conjunction to mitigate. Similarly, and more often the case, they also represent a conjunction that can be avoided during station-keeping based on Pc. In 2020, the share of actionable CDMs remained well over 95%. In 2023 and 2024, the share of these actionable CDMs occasionally dips far lower with the most significant dip to date being the May 2024 geomagnetic storm. During these periods, a significant portion of conjunctions are evaluated as low risk not because they are without risk but because their errors are too great. Likewise, station-keeping performed near these may inadvertently later create events that trigger criteria once those errors recover to usable values. Such issue in the source CDMs, fault of predicting solar behavior, is the origin of "no-maneuver" events recently observed even after the retirement of block 1 (Fig. 2).

The number of avoidance maneuvers is thus affected during solar max due to the positive influence of opportunistic station-keeping and the negative influence of increased orbit propagation errors. The period of reduced events in 2021-2022 when solar activity is rising suggests a sweet spot in this balance of station-keeping opportunities and the solar variability detrimental to orbit prediction.

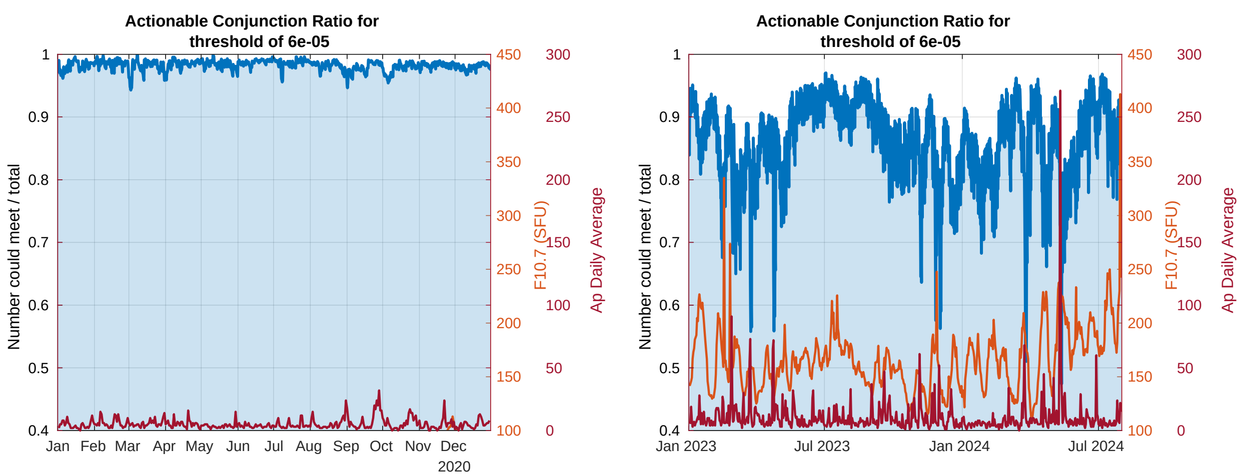

Figure 3: A conjunction is potentially actionable or usable if the covariance creates a Pc over a threshold of interest at a zero miss distance. In this Pc-zero metric, the miss distance is set to zero and the Pc recomputed to test against the threshold for all conjunctions within 72 hours of TCA. During periods of solar activity with rapid changes to atmospheric density, the share of actionable conjunctions decreases. During the May 2024 storm, the percent of actionable conjunctions briefly dropped to 47%.

5. OPPORTUNISTIC STATION-KEEPING

From first launch in 1997, the first 12 years of Iridium operations did not have data for collision assessment and avoidance, so station-keeping objectives were limited to staying within the control box and maintaining a frozen orbit. Block 1 operations began with automated maneuver planning aboard the satellite, which was triggered by orbit estimation updates from the ground. When solar activity subsided in 2007, onboard maneuver planning transitioned to the ground. The block 1 satellite's thrusters were all posigrade and solar radiation pressure on the main mission antennas raised the semimajor axis during periods of low atmospheric drag[2]. The station-keeping strategy changed

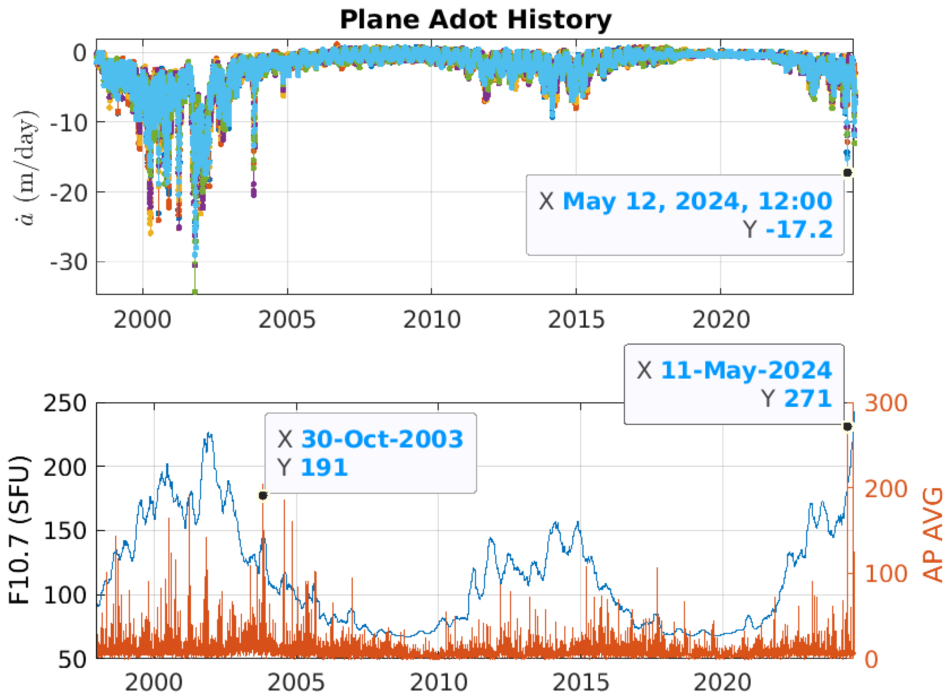

Figure 4: Measured drag as a daily change in semimajor axis and solar indices for the history of the Iridium constellation. The May, 2024, geomagnetic storm was the most significant activity since 2003.

from independent satellite-centric maneuvering to flying planes together, maintaining relative intra-plane separations.

On February 10th, 2009, COSMOS 2251 and Iridium 33 collided following a plane re-clustering maneuver[11]. The collision changed government data sharing policies, allowing for actionable collision assessment later in February with the first conjunction of concern on February 23rd. The first collision avoidance maneuver was conducted on April 27th. During the first few years, the use of collision screenings was limited to avoidance maneuvers due to the small "pizza box" screening volume of 200 meters radial, 1-kilometer intrack and crosstrack. However, these small volumes also led to surprise conjunctions and allowed conjunctions of concerning probabilities to occur outside the screened volume. Addressing these concerns led to the 95% capture volume in 2012, defined by NASA CARA[8], requested by Iridium, and granted to all operators cooperating with the then Joint Space Operations Center (JSpOC) and 18th Space Control Squadron. The volume expanded again by 2019 for operator ephemerides screenings to accommodate maneuvers and maneuver errors. The current volume is 2 km radial, 25 km intrack and crosstrack.

From 2012 on, larger volumes provided enough information on the local conjunction environment to perform opportunistic station-keeping. Instead of just emergency maneuvers or binary station-keeping decisions, nominal station-keeping maneuvers could be tweaked to reduce risk. Starting in 2017, Iridium's block 2 launched, refreshing the full constellation by 2019 with new vehicles equipped for uninhibited retrograde and posigrade maneuvers within the control box. Unlike block 1, block 2 has not only posigrade but a retrograde thruster and can maneuver, without attitude motion that interferes with communication links, in the direction best suited to mitigate a conjunction.

The mechanized station keeping process (automation with human approval or initiation) seeks to minimize the aggregate probability of collision of each vehicle while remaining within a control box of +/-18 km along track and maintaining a frozen orbit[12]. The recent efficacy of the approach is considered for the maneuvers conducted since early 2023, when the latest version was implemented and representing a period of higher solar activity.

Iridium defines a maneuver as a sequence of burns created at the same epoch, where each burn consists of thruster pulses spaced close enough in time that orbit change calculations are effectively achieved with impulsive ΔV. Maneuvers can last days, though most station-keeping is complete within a day, currently conducted as 1 burn per orbit (rev) for Iridium block 2, lasting no more than 20 revs. A possible definition of maneuver that would transcend finite or continuous thrusting is that the defining components were created at the same epoch. Changes to a maneuver strategy would be a new maneuver. Maneuvers in this paper are the set of burns created at the same time.

While the resulting probability of collision for each burn could be considered, maneuvers that cross an intersection with another object will initially increase risk before crossing and then, ideally, proceeding further to decrease risk over the initial state and before the time of the intersection. Though favoring that operational satellites should NOT cross their mutual intersection but always move away[13], the strategy both limits acceptable risk solutions in an aggregate environment and prevents coupling station-keeping with risk reduction when the intersection is behind the satellite. For debris, Iridium therefore does not restrict maneuvers from crossing the intersection. For the sake of understanding risk reduction, maneuvers will thus be considered as a whole, comparing only the start and end of each.

The probability of collision is assessed using the 2D Pc via Elrod[3], which is effective for almost all conjunctions experienced by Iridium. Operationally, numerous other methods including scaled Pc, a Pc 3D and Brute Force Monte Carlo are used, but for the sake of limiting the dimensions to explore over a large data set, Pc Elrod is used. Furthermore, for the analysis here, the hard body radius for Iridium is set to the conservative maximum value rather than assessing the individual solar array positions and projected area per conjunction as done operationally by the station-keeping algorithm.

Iridium also currently implements a delay between maneuver creation and maneuver execution to externally announce the intention to maneuver. Currently, this offset is 8.5 hours for nominal station-keeping or 45 minutes for COLAs. If warranted, the burns could be withdrawn or changed during this second delay between maneuver creation and maneuver execution. These caveats noted, for practicality, the CDM creation time before burn execution is used in this analysis.

The immediate result of each maneuver is depicted in Fig. 6 with the Pc using data immediately after the conclusion of a maneuver (always new Iridium data for the primary, sometimes new estimates of the secondary, particularly after longer maneuvers). Data below the line of unity slope is preferred, representing maneuvers that decrease risk. The plot contains all future conjunctions between maneuver end and the start of the next maneuver or a maximum of the 7-day screening, so some conjunctions of concern naturally evolve to lower risk before TCA.

To capture the final known risk close to the last actionable time one rev before TCA, the last CDMs before TCA were used with the last Iridium states before TCA. An implementation drawback of the approach is the creation time of the CDM is used; however, the delay between creation of the CDM and transmission to Iridium was not easily recoverable. That delay is sometimes significant with CDMs of concern available after TCA. A hypothetical ephemeris without the maneuver, using the observed drag force on the satellite, was used as a comparison. The change in decibels for the aggregate probability of collision between these states is shown on the right in Fig. 6. Implied by both figures is an entanglement of station-keeping and the number of perceived COLAs.

When opportunistic station-keeping works well, a race condition exists for Iridium's traditional alert event metrics. If the COLA process acts first, it's a mitigated conjunction with a maneuver; if the station-keeping process runs first, it's a nominal maneuver outside the counting.

6. HOW THEN TO COUNT COLAS CONSISTENTLY?

Historically, Iridium's collision avoidance maneuvers were categorized by Pc threshold, though a miss distance of 100 meters was applied as a safety net for large secondary objects as a hedge against any issue with covariance realism. Though applying a rule set with automation determining alerts, the data at times in Fig. 2 may still occasionally contain human bias in applying those rules and labeling the COLAs. For the most part, the data follows the rule set with the exception that there is a judgment call labeling nominal station keeping burns that effectively mitigate conjunctions that meet the criteria. If a station-keeping burn addresses a conjunction of concern, does it count as a COLA maneuver or station-keeping? Station-keeping when automation determined it? A COLA only when a human operator intervenes? What if the two are not easily separable or maneuvering fully automated? How do we account when station-keeping algorithms already seek to minimize the aggregate probability of collision? With the implementation, and continued refinement, of station-keeping that seeks to minimize the probability of collision, other metrics to count COLAs may be better for historical trending.

As enumerated in Table 2, possibilities include necessary maneuvers that violated mission constraints, required non-

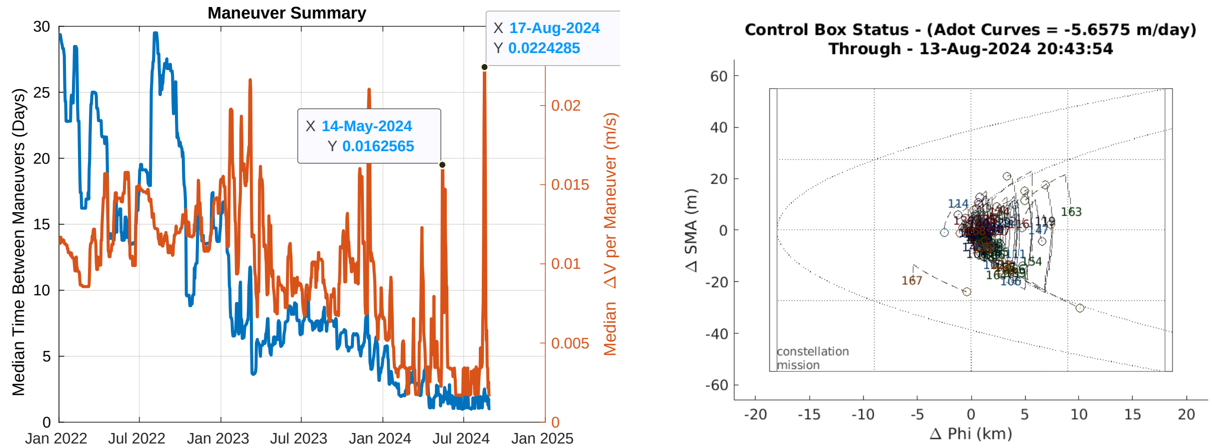

Figure 5: Median maneuver frequency and magnitude for mission vehicles on the left with example of control box motion on the right. With higher solar activity, the cadence has been adjusted for more frequent smaller maneuvers. Geomagnetic storms, such as the G5 May 13-15 and G2 activity August 11-14, drive subsequent larger maneuvers over the baseline.

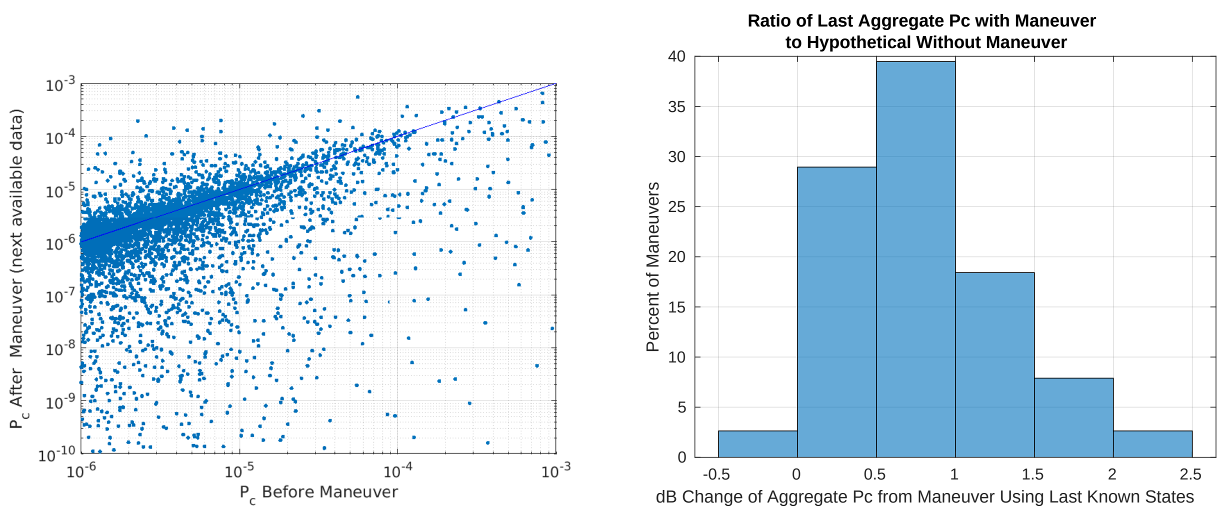

Figure 6: The achieved Pc before and immediately after the maneuver and the achieved aggregate Pc improvement later using the last available data prior to TCA. Note the plot on the left contains data that may still be evolving as additional measurements advance knowledge towards TCA. It is not the final known risk. The plot on the right is the best that can be known with the last measurements shared (ideally but not always before TCA).

nominal action, entailed additional risk to the mission, or expended additional resources such as fuel. Two of these, violation of mission constraints and additional risk to the mission, are captured as retrograde maneuvers during block 1 operations. Block 2 added a retrograde thruster to prevent both cases. Maneuvers that required action outside nominal procedures appears difficult to define in a manner that could be applied not only across operators but across time. The assumption is that most operators act like Iridium with a mantra of constant operational improvement. What qualified as an emergency yesterday doesn't qualify as an emergency today. Corrective or proactive action addresses future occurrences.

That reasoning, at least from an Iridium mind set, leaves maneuvers that consume extra resources as a metric that could be useful. As Iridium maneuvers are mechanized (or automated with human approval or initiation), the principal resource consumed beyond mission objectives is fuel. Albeit tiny during the mission phase, the concept is at least measurable. Iridium maintains its satellites within a control box as depicted in Fig. 5. Atmospheric drag is the principal disturbing force, pulling the altitude down and then countered by the posigrade thrusters to cycle through the control

Table 2: Ways to standardize COLA designation

Method	Pro	Con
Conjunction exceeds a Pc threshold	Seemingly simple and the principal rule Iridium has used to designate COLAs	Conflated with station-keeping maneuvers that were not intended solely for COLA.
Maneuver violated mission constraints	Captures cost in detriment to mission objectives	Not equivalent across missions; cross-comparison difficult
Maneuver required action outside nominal procedures or entailed additional risk to the mission	Captures "Emergency"	Metric tied more to issues in operations that can be corrected. Not equivalent across missions; cross-comparison difficult
Maneuver expended extra fuel beyond mission objectives	Easy to evaluate. Captures cost to satellite. Comparable at similar altitudes.	Not comparable across altitudes

box. Opposing atmospheric drag is fuel spent towards the mission objective. Maneuvers that mitigate conjunctions only consume additional fuel if a retrograde maneuver is required to remain within the control box. If a posigrade maneuver is sufficiently small, atmospheric drag naturally returns the satellite back to the target altitude before the satellite exceeds the along-track tolerance. If a posigrade avoidance maneuver is too large, a corrective retrograde maneuver is required, and fuel beyond the station-keeping budget for atmospheric drag is consumed. Likewise, any conjunction requiring a retrograde maneuver consumes additional fuel.

Applying this metric of additional fuel consumption to the Iridium history tracks with the change in collision mitigation reluctance between Block 1 and Block 2. Very few block 1 maneuvers labeled as a COLA required a retrograde maneuver either subsequently or as part of the initial COLA, clearly reflected in the category of “no maneuver” more numerous for the first half of Fig. 2. During block 1, these retrograde maneuvers would also have met the other possible categories of violating mission constraints (pointing all antennas the wrong directions) and additional risk (flying upside down and out of contact with the ground). For block 2, these concerns were removed by design. COLAs are decoupled from mission constraints resulting in less inhibition. Extra fuel is now consumed for roughly half the conjunctions identified by the traditional threshold metric.

Fortunately, station-keeping and COLAs are minor consumers in the fuel budget, which is dominated by usage for the initial ascents from injection orbit to mission, RAAN drift maneuvers, and deboost from orbit at end of life. Still, consumption of fuel for COLAs is one way to record extra effort required by a conjunction. Moreover, it addresses the question of arbitrarily assigning station-keeping maneuvers as COLAs or station-keeping. If all maneuvers seek to minimize the aggregate probability of collision, perhaps only the ones that required extra fuel should count as COLAs.

Fig. 7 shows a comparison of the current action metric versus one based on fuel usage. To account for the "non-maneuver" instances occurring during geomagnetic storms, they are included despite not using fuel. Traditionally, Iridium has used the simple metric of conjunctions meeting criteria within 72 hours of TCA, based on the criteria in Table 1. Station-keeping activity is hiding events that would have been called a COLA had collision assessment always preceded station-keeping maneuver creation. With opportunistic station-keeping handling a portion of risk mitigation, a consistent capture agnostic of agent is the fuel usage.

7. CONCLUSION

In the realm of collision assessment, three types of metrics were discussed. The first, a simple count of conjunctions within screening criteria, is not a direct metric of risk as the number was shown to actually yeild a benefit in large numbers–particularly when much larger than the subset that creates the alerts, the second discussed. Beyond trending and avoiding surprise conjunctions, the extra data created an opportunity that influences the third metric of how to count the events of concern. Opportunistic station-keeping that seeks to minimize the aggregate probability of collision subtracts risk that nominally would be labeled as a COLA, suggesting new thinking of how to count conjunction concerns. A count of times extra fuel was consumed is a promising means to do that.

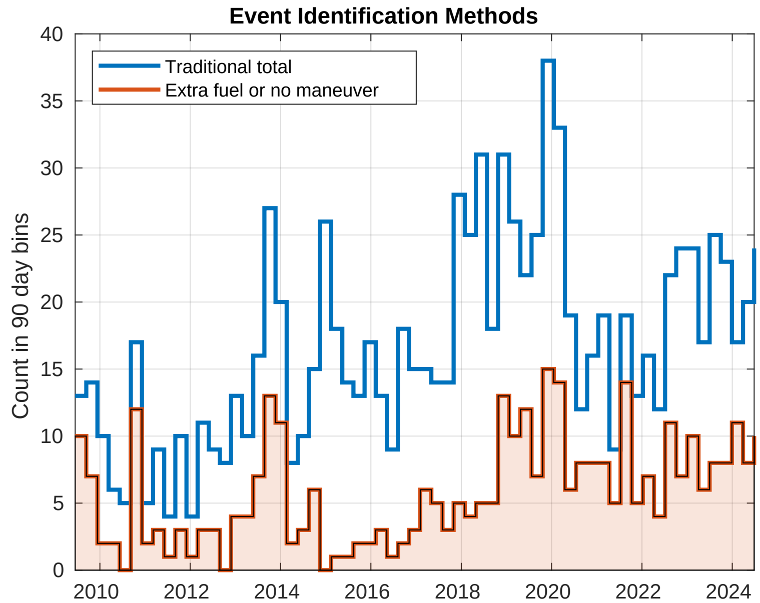

Figure 7: Two alternative conjunction criteria for categorizing compared to traditional.

8. FUTURE CONSIDERATIONS

The DoC upcoming deployment of TraCCS promises to upgrade collision screening and assessment beyond the existing DoD solution, offering new avenues of collaboration and transparency. The aim to increase screening cadence and response times can improve risk reduction, but the size of the screening volume itself should be an important consideration for situational awareness and the efficacy of opportunistic station keeping. A large screening volume enables efficient optimization of maneuvers by providing all the data for all the needed function calls at the same time.

Absent a specific focused definition, this review of Iridium's own history also shows conjunction alerts and COLAs to be metrics with multiple possible dimensions in the interpretation. While improved transparency will aid such understanding, events reported as a requirement from licensing may not represent singular insight.

9. REFERENCES

[1] Space Safety Coalition. Best practices for the sustainability of space operations. https://spacesafety.org/, August, 2023.

[2] G.L. Dixon, W.H. Boyce III, and Ryan W. Shepperd. Investigation of solar pressure effects at Iridium mission altitude and solar sailing mitigation techniques. *NASA Goddard Symposium*, October, 2003.

[3] Chris Elrod. *Computational Bayesian Methods Applied to Complex Problems in Bio and Astro Statistics*. PhD thesis, Baylor University, 2019.

[4] FCC. Globalstar license LLC application for modification of non-geostationary mobile satellite service system authorization. (DA 24 825), August 16, 2024.

[5] M. Hejduk, F. Laporte, M. Moury, T.S. Kelso, L. Newman, and R. Shepperd. Consideration of collision "consequence" in satellite conjunction assessment and risk analysis. Presented at 31st International Symposium on Space Technology and Science (ISTS), 26th International Symposium on Space Flight Dynamics (ISSFD), and 8th Nano Satellite Symposium (NSAT), 2017.

[6] Iridium, OneWeb, and SpaceX. AIAA satellite orbital safety best practices, September, 2022.

[7] Travis F. Lechtenberg. An operational algorithm for evaluating satellite collision consequence. Number AAS 19-669, 2019.

[8] Steven Narvet, Ryan C. Frigm, and M.D. Hejduk. Assessment uncertainty-based screening volumes for NASA robotic LEO and GEO conjunction risk assessment. (AAS Paper 11-432).

[9] NASA. *NASA Spacecraft Conjunction Assessment and Collision Avoidance Best Practices Handbook*. Number NASA/SP-20230002470 Rev 1. Office of the Chief Engineer, February 2023.

[10] Office of Space Commerce. TraCSS listening session: DoD-DOC space traffic coordination ops transition. https://www.space.commerce.gov/tracss-listening-session-on-considerations-for-dod-doc-space-traffic-coordination-ops-transition/, Feb 20, 2024.

[11] Ryan Shepperd. Subsequent assessment of the collision between iridium 33 and cosmos 2251. *24th Advanced Maui Optical and Space Surveillance Technologies Conference*, September, 2023.

[12] Ryan Shepperd and Kristina DiOrio. The evolution, de-evolution, and re-evolution of iridium automated satellite station-keeping. Presented at International Conjunction Assessment Workshop, 2023.

[13] Ryan W. Shepperd and Kristina C. DiOrio. The time for a set of traffic rules has arrived. In *Astrodynamics 2020, Advances in the Astronautical Sciences*, volume 175, August 9-12 2020.