



Operators' Requirements for SSA Services

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Abstract

The space data association (SDA), an association of global satellite operators working to ensure a controlled, reliable, and efficient space environment, has run a survey among its members to gather data on their Conjunction Assessment concept of operations. These include collision avoidance Go/No-Go metrics, collision avoidance targets, and operational constraints. This paper assesses the various positional accuracy requirements of space situational awareness (SSA) data associated with each of these diverse "Go/No-Go" metrics as employed in the conjunction mitigation processes used for space traffic coordination and spaced traffic management. These metrics include miss distance at the time of closest approach (TCA), componentized miss distance (e.g., TCA radial separation to preclude collision even when in-track or cross-track separations or uncertainties are unknown), and maximum collision probability and estimated actual probability. A common practice is to approximate a spacecraft's hardbody with an encapsulating sphere. This one-shape-fits-all approach eliminates the need to determine orientation, but results in an overestimated object volume and an overinflated probability unless both satellites are actually spheres. The dependence of collision probability on orientation and configuration/shape of the satellites at TCA is examined in contrast to the use of an encapsulating spheres to produce more representative probabilities. To overcome the lack of knowledge of the enveloping box's orientation a spectrum of collision probability values corresponding to a range of box orientations, from which the interrelationship between attitudinal knowledge and position accuracy required for a given collision probability threshold can be determined. It was found that such an approach can typically reduce probability by a factor of 3 or more. The interrelationships between SSA positional accuracy, the operator-selected Go/No-Go metric and its threshold, timeliness, and resulting maneuver frequency is also explored. For example, the necessity to perform a collision avoidance maneuver adhere to a squared relationship on the adopted miss-distance threshold. The miss distance threshold adopted by the operator should, if done properly, be a function of the estimated accuracy of the primary and secondary objects as a function of time. This paper concludes by

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comparing the accuracy requirements derived for each metric above with estimates of positional accuracy observed in actual SSA data fusion experiments conducted this past year. In many situations, the accuracy of legacy and commercial SSA systems is insufficient to support the adopted Go/No-Go metric without using comprehensive data fusion techniques. Recommendations for operators are provided.

Keywords Space situational awareness · Space traffic · Coordination · Management · Accuracy requirements · Conjunction assessment

1 Introduction

Spacecraft operators employ diverse close approach metrics and standoff distances when determining whether a collision avoidance maneuver is warranted. Typically, operators with spacecraft in a low-risk orbital regime may implement ultra-conservative collision avoidance strategies at little fuel or operations cost, while operators with spacecraft operating in high-risk regimes are forced into economical collision avoidance strategies to avoid depleting their fuel budget and overtaxing their flight dynamics teams.

Unfortunately, while many collision avoidance maneuver Go/No-Go criteria exist, operators are often unable to obtain the space situational awareness (SSA) information and SSA accuracy necessary to populate the criteria that suit them best. Additionally, the algorithms used to populate these criteria sometimes contain invalid assumptions such as using linearized relative motion and spherical object shape approximations when more sophisticated formulations are required. And while some sources exist for estimated satellite object dimensions, the relative attitude at the time of conjunction may be uncertain or even unavailable, particularly for the so-called “secondary” or conjuncting object.

In an ideal world, a satellite’s configuration, orientation, and future position would be known with absolute certainty. If two satellites were predicted to touch, the probability of collision (P_c) would be one, else P_c would be zero. Lamentably, such a world does not yet exist. Surveillance and tracking sensors are imperfect, as well as orbit propagation techniques. With imperfect knowledge, estimating the possibility of a collision requires making some simplifying assumptions. Typically, spheres are used in the absence of satellite configuration/orientation information, and covariance is used to estimate positional uncertainties resulting in an entire range of collision probabilities. In the absence of covariance, miss distance screening and/or maximum probability [1, 2] is used.

Historically, space flight safety and related aspects have had to be accomplished in a data-limited environment [3]. In the early days of space object tracking, the single SSN accuracy requirement was that the object be tracked with sufficient accuracy that “track custody” would be maintained. Over time, SSN tracking accuracies continued to improve—but not necessarily commensurate with the increasing and diverse ways that the space community found to use and incorporate this information. The space operations community, while very appreciative of any/all available

tracking data it can obtain, has had to accept the innate accuracies of the best-available positional data (TLEs, ephemerides that lack planned or historical maneuvers, lack of uncertainty information, unknown object sizes, shapes, orientations, masses, and materials) to operate spacecraft and avoid collisions.

While new government, civil and commercial initiatives are making great strides to address these shortcomings, the mindset of “making the best of the data on hand” remains the primary approach. Yet as was recently demonstrated in a Space Traffic Coordination and Management (STCM) demonstration, positional accuracy of current SSA products often is insufficient to be used in the way that operators are using it. The mindset needs to evolve to consider (a) what metrics and thresholds are required to promote space flight safety and long-term sustainability of space operations; (b) what positional accuracies do such metrics and thresholds require in order to be actionable; and (c) what sensor laydowns, data fusion processes, data exchange, orbit determination methods, covariance realism, and orbit propagation techniques are required to ensure that the resulting positional accuracy requirements are amply met.

Accuracy requirements with respect to conjunction avoidance parameters have been presented in several papers [4, 5] and nicely summarized by Sánchez-Ortiz and Krag [6]. Those works examine the number of false alerts per year as well as risk reduction through sensor improvements. This work differs from those in that the concept of maximum probability is employed to determine minimum accuracy required at the time of closest approach (TCA). Required accuracy at orbit determination epoch can then be deduced by backwards-propagating the covariance in an orbit-dependent manner.

The following sections describe the space data association (SDA) operator survey Go/No-Go metrics, address the dependence of collision probability on object shape and orientation, examine positional accuracy requirements, and investigate maneuver frequency dependencies. Additionally, some SSA data fusion experiment findings are discussed.

2 Collision Avoidance “Go/No-Go” Metrics

When a spacecraft operator selects metrics and corresponding thresholds to help them judge when an upcoming close approach is too close for comfort, they likely incorporate not only their operational knowledge, but also the complexity and computational resources required to assess the metric, input data required by the metric, the amount of regime crowded, flight dynamics and management staffing, corporate and cultural considerations.

One might tend to think that operators have evolved to a consensus, standardized view of what Go/No-Go metric to use. Yet there are today numerous metrics, and even combinations of metrics, that operators employ. The diversity of these metrics often is driven by the vastly different environments, mission funding levels, resources, and collision risks that a particular spacecraft (or operator) tends to face.

Spacecraft operators in all regimes often struggle to determine which conjunctions are “too close.” Operators with spacecraft operating in a low-risk orbital

regime can implement simple yet effective, ultra-conservative collision avoidance strategies at little fuel or operations cost. Operators with spacecraft operating in high-risk regimes must be as realistic and as “lean” in their collision avoidance strategies as possible to avoid depleting their fuel budget and overtaxing their flight dynamics teams. Unfortunately, while many collision avoidance maneuver Go/No-Go criteria exist, operators are generally unable to obtain the metrics and data types necessary to populate the criteria that suit them best. Additionally, the algorithms used to populate these criteria sometimes contain invalid assumptions such as using linearized relative motion and spherical object shape approximations when more sophisticated formulations are required.

While collision probability (P_C) has become a popular criteria when assessing conjunction threats in some orbital regimes, its use is certainly not universal. Unlike other singular methods such as Cartesian distance, Mahalanobis distance, maximum probability, or ellipsoids-touching tests, many operators prefer P_C -based action thresholds because P_C incorporates miss distance, covariance size and orientation and the sizes of the conjuncting objects in a mathematically rigorous fashion. Additionally, collision probability metrics can be compared on an equal footing with other failure scenario probabilities such as the probability that a thruster would “stick open.”

Yet widespread adoption of P_C by operators is ill-advised (and unlikely) for several reasons. First, the data required to assess P_C may either not be available, or not available at the accuracy required to obtain decision-quality P_C estimates. Second, operators may experience so few conjunctions (e.g., in MEO) that they have ample maneuvering fuel to take a more conservative approach such as the use of a miss distance threshold, greatly simplifying the analyses required of their flight dynamics staff.

With these thoughts in mind, consider the non-exhaustive list of Go/No-Go metrics operationally used by spacecraft operators for flight safety as provided in Table 1. There is a spectrum of criteria being used, ranging from ultra-conservative maximum probability metrics that are mathematically rigorous and quite useful when there are few conjunctions and maneuvering fuel is ample, to purely miss distance-based screening using arbitrary thresholds, to estimated actual P_C .

The notional “ratings” included in Table 1 were purely subjective, as judged by peers knowledgeable in the algorithms being used. At times, the rating is listed as a question mark “?”, denoting that a rating is not possible without knowing what the user selected as a threshold. Where possible, the table has been sorted by the estimated amount of maneuvering fuel required, with a value of ten denoting the least use of fuel. Nevertheless, they reveal a few interesting traits:

1. Metrics that are based upon arbitrary miss distance criteria, while quite simple to evaluate, provide an unknown level of “protection” and can be very inaccurate in portraying actual collision risk.
2. The criteria that are the simplest to evaluate and require the least amount of input data tend to require the greatest maneuvering fuel (and the greatest number of avoidance maneuvers).

Table 1 List of operationally used Go/No-Go conjunction screening criteria, characterized on a scale of one to ten

Collision avoidance Go/No-Go criterion	Conservatism (10 = most conservative)	Fuel usage (10 = least fuel)	Accuracy (10 = best risk portrayal)	Complexity and data required (10 = simple, little data)
Cartesian miss distance, arbitrary user threshold	*	*	1	10
Componentized miss distance, arbitrary user threshold (e.g., radial-only separation)	*	*	1	10
Combination of miss distance and estimated collision probability P_C (e.g., “F-factor” [7])	*	*	7	4
Max probability-based Cartesian miss distance	10	2	3	9
Eigenvalue-based componentized miss distance	8	4	4	4
Collision “consequence” metric [8]	5	5	6	3
Mahalanobis miss distance	9	5	3	4
Mahalanobis distance adjusted for spherical shapes (combined hard-body radius or CHBR)	9	5	5	4
P_C , linearized motion, spherical CHBR	8	7	7	4
P_C , non-linear motion, spherical CHBR	3	7	7	3
P_C , linearized motion, asymmetric body shapes	6	9	9	2
P_C , non-linear motion, asymmetric body shapes	1	10	10	1

*Dependent upon selected threshold(s)

3. The criteria that use the least amount of maneuvering fuel tend to be judged the most accurate in terms of quantifying the likelihood that a collision would occur.

Table 1 [7, 8] indicates that from a fuel usage standpoint, the most accurate form of collision probability assessment would serve as the best conjunction assessment metric. But collision probability assessment has its shortcomings as well. P_C should not be used as a Go/No-go metric without first fully understanding the potential inaccuracies, assumptions and pitfalls associated with it. Many of these are discussed in [9]. Of principal concern are:

- (1) Nominal trajectories may be inaccurate, primarily due to unforeseen (and therefore unmodelled) maneuver(s) on the part of either your satellite, or the object you're conjuncting with, but also due to other unmodelled forces and perturbations (e.g., space weather event or atypical attitude orientation or attitude maneuver etc.);
- (2) Covariance (error) information may be inaccurate or unavailable for either your satellite or the object you're conjuncting with;
- (3) Satellite relative motion may be "non-linear," violating the assumptions of the simpler P_C assessment methods [10];
- (4) The object shapes may be aspherical, violating the hard body radius assumptions of the simpler P_C assessment methods;
- (5) The hardbody size of your satellite might not be properly reflected in the assessment system;
- (6) The hardbody size of the object you're conjuncting with might not be known and/or properly reflected in the assessment system.

Each of these six concerns can lead to P_C estimates that are multiple orders-of-magnitude from the actual P_C estimates one would obtain if none of these principal concerns existed.

Once the operator has selected the metric that they want to use to assess how concerning an upcoming close approach is, the operator must select the threshold (or as will be seen in the next section, the combination of thresholds) that serve as the trigger for when to conduct a collision avoidance maneuver. In selecting the threshold(s) of concern, a spacecraft operator might consider such diverse aspects as:

- Importance of the mission (critical to human health/safety, military, communications, earth imaging, or merely educational, etc.),
- How long it may take to field a replacement spacecraft, should their current one be destroyed or impaired by the collision,
- How well-staffed an operator's flight dynamics team is to be able to process and avoid conjunctions,
- Frequency of close approaches (for example, if an operator's spacecraft rarely comes close to other spacecraft or debris, then that operator can afford to be quite conservative in their approach to guarantee that their spacecraft is safe without adversely impacting mission duration and depleting fuel prematurely),

- Public awareness and/or opinion,
- Investment, level of interest, and involvement of their shareholders,
- Cost of the spacecraft,
- Cultural aspects,
- Concerns over competitive ‘shaming’,
- Competitive advantage.

It is easy to see from this diverse list how operators may employ diverse metrics and thresholds. As an aside, note that such considerations as the long-term sustainability of space activities, while certainly very important to many commercial companies, may not be a top consideration for some companies when selecting their metrics and thresholds. And the thresholds that the operators select may primarily be targeted at ensuring the safety, security, and availability of their individual spacecraft and mission services, as opposed to ensuring global space safety.

3 SDA Operators Survey

With those things in mind, it is useful to “take the pulse” of the spacecraft operator community to see what Go/No-Go metrics and thresholds are actively being used today. One approach to obtaining such information is by surveying operators that participate in an industry-formed association.

The space data association (SDA [11]) is an association of satellite operators which has the primary goal of mitigating the risk of proximity operations and facilitating operational coordination among its members. The SDA comprises 32 operators in all orbital regimes (LEO, MEO, and GEO). These operators agreed to pool their operational data to perform ephemeris-vs-ephemeris conjunction assessment using best accuracy data. The need for the SDA existence arises from the fact that no single SSA service has all the data needed to accurately assess conjunctions. They do have reliable estimates of the orbit of debris, but they do not usually have access to the maneuver plan of active satellites, which significantly alter the orbit. The SDA created the Space Data Centre to fuse data provided by the 18th SDS on debris with operational data provided by the operators themselves. The Space Data Center currently performs flight safety assessments for 274 GEO satellites (over half of all active satellites in GEO). Additionally, 475 LEO/MEO satellites are handled by the SDA, which performs conjunction assessment runs several times a day.

The SDA supported the US Department of Commerce (DoC) in the design of a Pilot Project in the field of Space Surveillance and Tracking. This Pilot Project was expected to be preparatory to the development of a full-scale service that could take over the Conjunction Assessment service role currently performed by the 18th Space Defense Squadron (18th SDS).

In the framework of this activity, the SDA has collected anonymized information about the Collision Avoidance Concept of Operations (CA ConOps) of its members. The idea was to understand what performances a new system should deliver to help operators in their everyday job of Conjunction Assessment and Collision Avoidance.

Collision Avoidance operations are always platform-dependent, so each operator effectively has a different CA ConOps for each type of spacecraft. For this reason, the SDA also collected anonymized data on the maneuver capabilities of Members' spacecraft.

The SDA gathered voluntary feedback from 13 GEO operators (10 commercial and 3 institutional) and 7 LEO operators (5 commercial and 2 institutional). LEO is here defined as satellites orbiting at an altitude comprised between 400 and 2000 km. The operators who responded to the survey are collectively responsible for 200 GEO satellites and 394 LEO satellites. The main purpose of the survey was to understand what criteria the operators use when deciding whether or not to perform a collision avoidance maneuver, what are the main challenges in executing such operation, and what is the outcome that the operator is trying to achieve.

The survey was limited to SDA members only; non-SDA operators were not included. Although limited in scope, the existing results were quite revealing and compelling in their own right. In what follows, the main results will be presented and commented.

3.1 High-Interest Close Approaches

Question Which parameters do you monitor, and which thresholds do you use to decide whether a conjunction event is of high interest?

This question is asking operators to elaborate on when a conjunction warning prompts further analysis from the operations team. This does not necessarily translate into executing a collision avoidance maneuver, as there is the possibility to reshuffle station-keeping maneuvers in such a way to change the geometry of the encounter.

3.1.1 GEO Results

Some operators monitor exclusively the miss-distance, analyzing any event that results in an object entering a spherical volume centered on the spacecraft. These operators usually use 10 km as the sphere diameter, the default value for deep-space mission screening used by the 18th SDS [12].

Most operators use a combination of different parameters. The most common parameter monitored together with the tridimensional miss-distance is the radial component of the miss-distance because it is usually the one with the lowest uncertainty. Only a few operators among those contacted have decision criteria that consider also the along-track and cross-track components of the miss-distance.

Approximately half the operators contacted monitor statistical parameters together with geometrical parameters. Historically, the probability of collision has not been included in GEO CDMs, but the SDA provides the maximum probability of collision [1], and some operators make their own estimates of the probability of collision by introducing assumptions on the dimensions of the secondary object.

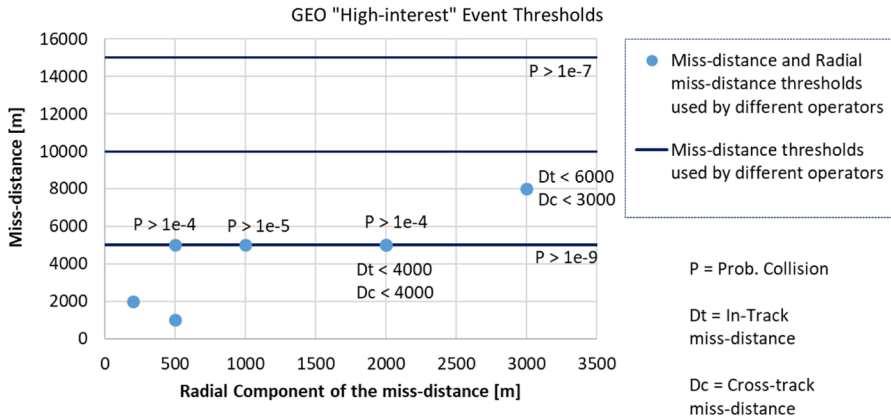


Fig. 1 GEO “high interest” event thresholds

The actual values of the monitored parameters that trigger higher conjunction warning scrutiny differ from operator to operator, and depend on their concept of operations, staffing constraints, satellites capabilities, and orbit determination performances. The results for GEO operators are summarized in Fig. 1 and Table 2. As seen from Table 2, not all of them responded with quantitative values.

The parameters monitored and thresholds used vary greatly among operators. This reflects considerable differences among operators in terms of concept of operations and risk tolerance. The operators who responded to this question use:

- Tridimensional miss distance in the range [1–15 km], with a median of 5 km;
- Radial component of the miss distance in the range [0.2–3 km], with a median of 1 km;
- Probability of collision in range [10^{-9} – 10^{-4}], with median of 10^{-5} .

3.1.2 LEO Results

There is more consensus among LEO operators regarding the parameters to monitor and the values used to trigger further analysis. The results for GEO operators are summarized in Fig. 2 and Table 3.

All the responding operators monitor the probability of collision. This is because LEO CDMs already provide these estimates. A majority of those responders also monitor the tridimensional miss-distance. None of the operators reported monitoring any parameters other than these two.

Most LEO operators use values in the range [100–1000 m] for the tridimensional miss-distance, and [10^{-5} – 10^{-4}] for the probability of collision.

The median value of the probability of collision for “high-interest” events in LEO is 10^{-5} , which might suggest that LEO operators have a greater risk tolerance than GEO operators. This might be due to the fact that the LEO regime is more crowded than GEO, so using LEO thresholds similar to GEO would result in a sizeable workload increase and a considerable amount of spent fuel.

Table 2 GEO “high-interest” event thresholds (each column represents an operator)

	GEO 1	GEO 2	GEO 3	GEO 4	GEO 5	GEO 6	GEO 7	GEO 8	GEO 9	GEO 10	GEO 11	GEO 12	GEO 13
Probability of collision $\geq P$		1.00E-04	1.00E-07	1.00E-05	1.00E-05	1.00E-04						1.00E-09	
Max probability of collision (SDA emails) $\geq P$		1.00E-04	1.00E-05	1.00E-05									
Tri-dimensional miss distance $< D$		5000	15,000	5000	10,000	5000	8000	2000	5000	10,000	1000	5000	
In-track component of the miss distance $< Dt$							6000		4000				
Cross-track component of the miss distance $< Dc$							3000		4000				
Radial component of the miss distance $< Dr$		2000		1000	500	500	3000	200	2000	500			
Combination of two or more of the above parameters	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES

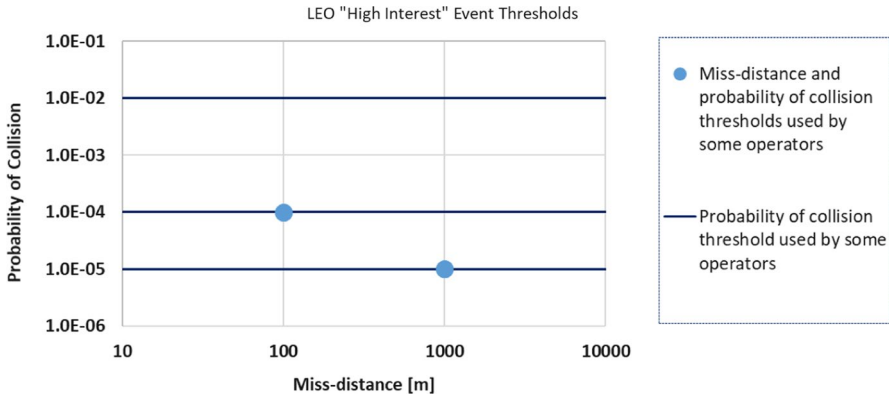


Fig. 2 LEO “high interest” event thresholds

Operators whose fleet is non-maneuverable represent an exception. The only means these operators have of mitigating the risk of a close approach is by executing an attitude maneuver and relying on differential drag to modify the satellite orbit [13]. These operators usually need to interrupt the mission of their satellites for the duration of these maneuvers, which can last several days. For this reason, these operators tend to use higher thresholds for the probability of collision. In the SDA survey, a value of 10^{-2} was reported.

3.2 Collision Avoidance Maneuver Execution Time

Question If you have ever executed a (chemical, electric, or else) maneuver specifically designed for Collision Avoidance, what is your preferred maneuver execution time with respect to the Time of Close Approach (TCA)?

This question is important to assess operators’ decision loop timing for Collision Avoidance. There are two schools of thought. Some operators act as early as possible to mitigate the risk of close approach well before this risk results in a high probability of collision. Other operators wait as long as possible to refine the available data and get a better estimate of the geometry of the encounter and its risk level. The spacecraft’s propulsion system clearly affects the concept of operations, as the next section will show.

3.2.1 GEO Results

The preferred execution time for a Collision Avoidance maneuver, as reported by GEO operators, is summarized in Fig. 3,

As Fig. 3 shows, the preferred execution time for a Collision Avoidance maneuver in GEO is usually between 0.5 and 2.5 days before TCA, with a median value at 1.5 days. This is because the collision avoidance maneuver is usually an in-plane

Table 3 LEO “high interest” event thresholds (each column represents an operator)

	LEO 1	LEO 2	LEO 3	LEO 4	LEO 5	LEO 6	LEO 7
Probability of collision $\geq P$	1.0E-04	1.0E-05	1.0E-04	1.0E-02	1.0E-05	1.0E-05	1.0E-04
Max probability of collision (SDA emails) $\geq P$		1.0E-05		1.0E-02			
Tri-dimensional miss distance $< D$			100		1000	1000	100
In-track component of the miss distance $< Dt$							
Cross-track component of the miss distance $< Dc$							
Radial component of the miss distance $< Dr$							
Combination of two or more of the above parameters		YES			YES	YES	YES

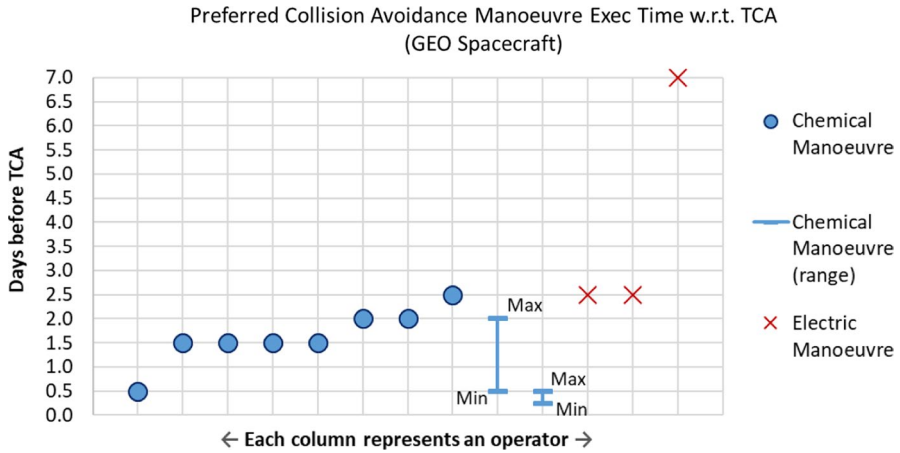


Fig. 3 GEO preferred collision avoidance maneuver execution time w.r.t. TCA

maneuver to increase the radial component of the miss-distance. Only one operator explicitly declared also using out-of-plane maneuvers for collision avoidance purposes—in this case the execution time was 6 h before TCA in order to maximize the variation of the cross-track component of the miss distance. One electric propulsion spacecraft operator reported that collision avoidance is carried out 7 days before TCA. While this value is an outlier among those reported, it is worth remembering that most electric propulsion spacecraft plan the station-keeping cycle for a whole week, so this can introduce planning constraints.

3.2.2 LEO Results

A majority of the LEO operators contacted prefer to execute a Collision Avoidance maneuver about 72 h before TCA, independently of the propulsion system used, as Fig. 4 summarizes. One operator indicated the preference to perform chemical maneuvers around 6 h before TCA, while another scheduled electrical maneuvers about 24 h before TCA.

To properly mitigate the risk of close approaches, the survey results suggest that most of the responding LEO operators would require actionable data about four days prior to TCA. One operator simply indicated the preference to perform collision avoidance less than one orbital period before TCA (this data point is not shown in Fig. 4).

3.3 Collision Avoidance Manoeuvre Preparation

Question How many hours can pass between notification of an emergency and the execution of the collision avoidance maneuver?

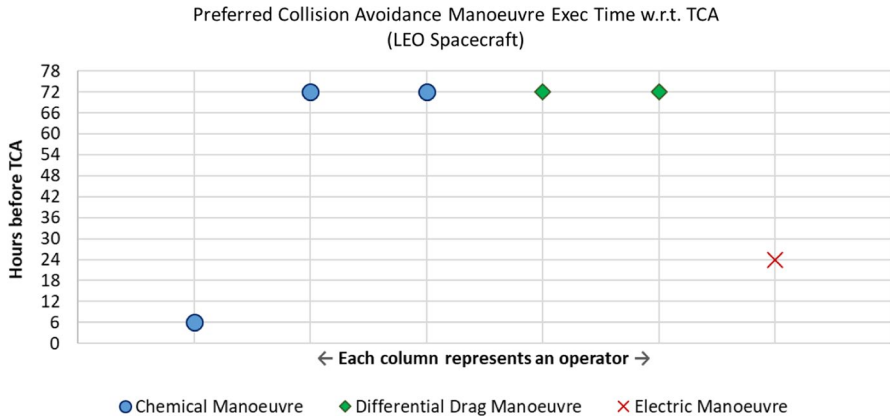


Fig. 4 LEO preferred collision avoidance maneuver execution time w.r.t. TCA

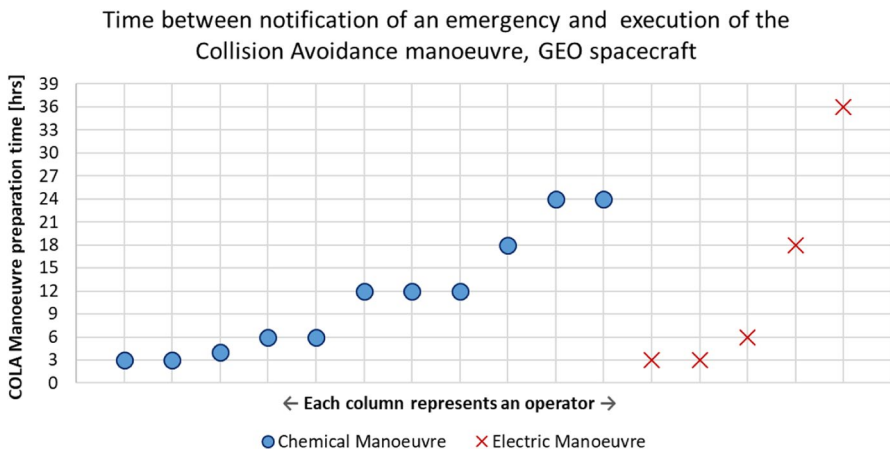


Fig. 5 GEO reaction time

This question essentially aims at estimating how long the reaction time can be after the notification of an emergency.

3.3.1 GEO Results

The responses on reaction time provided by GEO operators are summarized in Fig. 5.

As Fig. 5 shows, reaction time varies greatly among operators. This is likely depending on the concept of operations used. If the team assessing conjunctions and planning collision avoidance maneuvers works on 24/7 on-call shifts, then the reaction time can be quite short. If the team works on nominal working hours, then the reaction time can increase significantly, especially if the notification of the emergency is delivered during the weekend. All operators reported values between 3 and

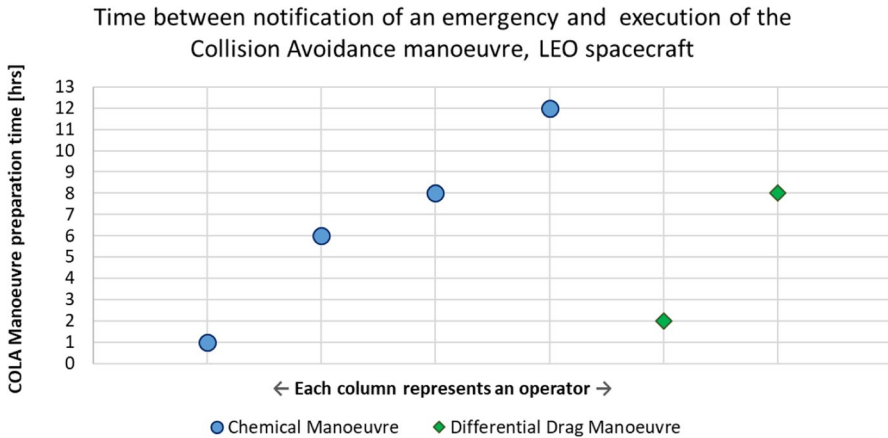


Fig. 6 LEO reaction time

36 h, and a majority reported a value of 12 h or less. There is no significant difference between the reaction time for chemical or electric propulsion.

3.3.2 LEO Results

All LEO operators who chose to answer this question reported response times equal to or lower than 12 h, without significant difference between the reaction time for chemical or differential drag maneuvers (Fig. 6).

3.4 Collision Avoidance Maneuver Targets

Question If you have ever executed a (chemical, electric, or other) maneuver specifically designed for Collision Avoidance, what parameter do you try to alter and which value do you try to obtain?

This question is essentially asking the operators to elaborate on when they would consider a high-interest event successfully de-risked. Mitigation is usually the result of reshuffling of planned maneuvers, deletion of maneuvers already commanded to the spacecraft, or planning a dedicated collision avoidance maneuver. To assess how the conjunction risk would evolve after implementing any of the aforementioned changes, operators would request updated estimates from the relevant conjunction assessment service.

3.4.1 GEO Results

Section 3.1.1 mentioned that there is no clear consensus among GEO operators on which condition defines a high-interest event. Similarly, there is no wide consensus on which parameters to target to mitigate the risk of close approach, as

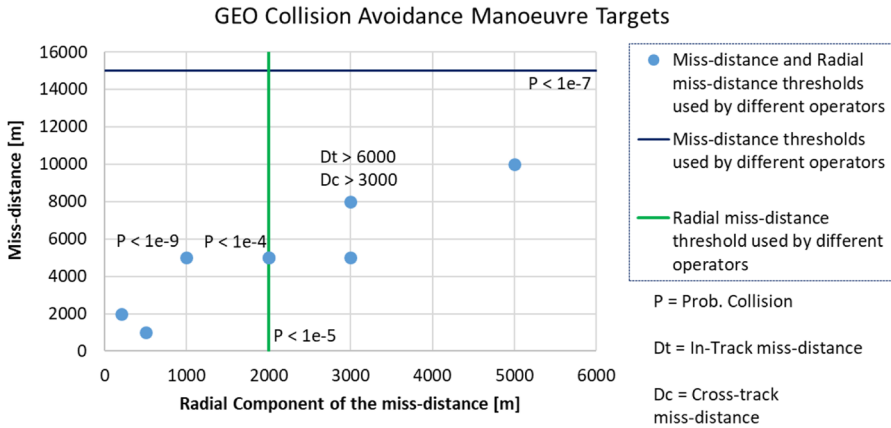


Fig. 7 GEO collision avoidance manoeuvre targets

Fig. 7 and Table 3 LEO “high interest” event thresholds (each column represents an operator) show.

The one thing that all GEO operators have in common is that they target at least one geometric condition (i.e., a certain value of the miss-distance and/or of one or more of its components). About half of the responding operators target both geometric and statistical conditions, i.e. they target a certain geometry and a maximum probability of collision. In summary, the operators contacted use these target values:

- Tridimensional miss distance in the range [1–15 km], with a median at 5 km;
- Radial component of the miss distance in the range [0.2–5 km], with a median at 2 km;
- Probability of collision in the range [10^{-9} – 10^{-4}].

A comparison of Table 4 and Table 2 suggests that GEO operators who monitor the probability of collision tend to use the same value for both threshold and target, i.e. they do not seek to achieve a P_C one order of magnitude lower than the value it had prior to the collision avoidance manoeuvre.

More than anything, Fig. 7 and Table 4 highlight the lack of consensus among operators on what is actually considered safe. This has multiple reasons. On one hand, the variety of concept of operations, spacecraft performances, staffing constraints, and risk tolerance can bring an operator to accept scenarios that would be unacceptable for others. On the other hand, there is a lack of agreed-upon guidelines that support operators in making these decisions, i.e. operators decide which metrics and thresholds to use, but there is no global entity telling them which metrics and thresholds they should be using.

Table 4 GEO collision avoidance maneuver targets

	GEO 1	GEO 2	GEO 3	GEO 4	GEO 5	GEO 6	GEO 7	GEO 8	GEO 9	GEO 10	GEO 11	GEO 12	GEO 13
Probability of collision $\leq P$	1.00E-04	1.00E-04	1.00E-07	1.00E-05									1.00E-09
Max probability of collision (SDA emails) $\leq P$	1.00E-04	1.00E-04	1.00E-05	1.00E-05									
Tri-dimensional miss distance $> D$	5000	5000	15,000	5000	5000	8000	2000	5000	10,000	1000	5000		
In-track component of the miss distance $> Dt$						6000							
Cross-track component of the miss distance $> Dc$						3000							
Radial component of the miss distance $> Dr$	2000	2000	2000	3000	2000	3000	200	2000	5000	500	1000		
Combination of two or more of the above parameters	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES

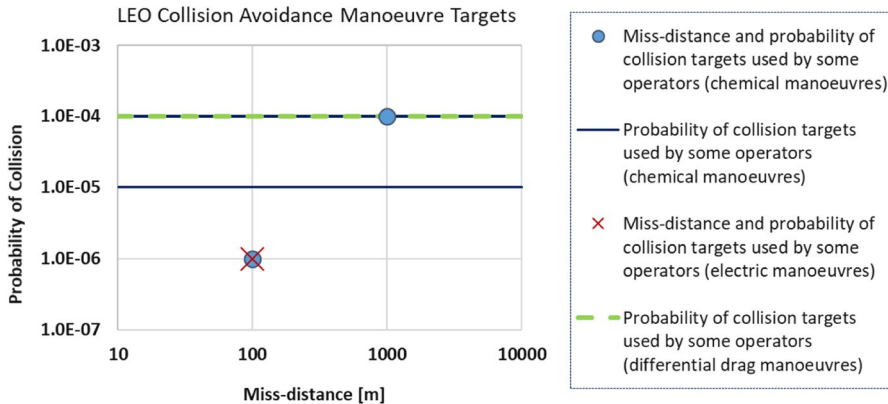


Fig. 8 LEO collision avoidance maneuver targets

3.4.2 LEO Results

The collision avoidance maneuver targets in LEO are fairly consistent among the responding operators. All of them target a certain probability of collision, while some of them also target a minimum miss-distance, as Fig. 8 and Table 5 LEO Collision Avoidance Maneuver Targets summarize.

All the operators target probability of collision between 10^{-6} and 10^{-4} . Half of them target a minimum miss-distance, with values in the range [100–1000 m]. There is no evidence to suggest that operators who execute a specific kind of collision avoidance maneuver (chemical, electrical, or differential drag) target values much different from those used by other operators.

Comparing Table 5 with Table 3 it is possible to infer that most LEO operators aim at a geometry after the collision avoidance maneuver that provides a probability of collision at least one order of magnitude lower than their definition of “high interest” event. There are exceptions, though, for which the target P_C is higher than the “high interest” threshold P_C . This suggests that these operators perform additional analyses on many conjunction data messages, but that those analyses don’t always result in implementing a collision avoidance maneuver.

3.4.3 Dependence of Collision Probability on Object Shape and Orientation

When performing conjunction analysis for short-term encounters, it is often the case that the orientation and configuration/shape of the satellites are unknown. As was demonstrated in [14, 15] the shape, size and dimensions of each of the two conjuncting space objects plays a critical role in the estimation of collision probability for a conjunction event. It is almost exclusively the case for debris objects. This necessitates certain assumptions when computing collision probability. A common practice is to approximate a spacecraft’s hardbody with an encapsulating sphere. This one-shape-fits-all approach eliminates the need to

Table 5 LEO collision avoidance maneuver targets

	LEO 1	LEO 2	LEO 3	LEO 4	LEO 5	LEO 6	LEO 7
PROPULSION	Chemical	Chemical	Chemical	Differential Drag	Differential Drag	Chemical	Electric
Probability of collision $\leq P$	1.0E-05	1.0E-05	1.0E-06		1.00E-04	1.0E-04	1.00E-06
Max probability of collision (SDA emails) $\leq P$							
Tri-dimensional miss distance $> D$			100			1000	100
In-track component of the miss distance $> Dt$							
Cross-track component of the miss distance $> Dc$							
Radial component of the miss distance $> Dr$							
Combination of two or more of the above parameters				YES		YES	YES

Fig. 9 Sphere of minimal volume touching all corners of a rectangular box enveloping the satellite

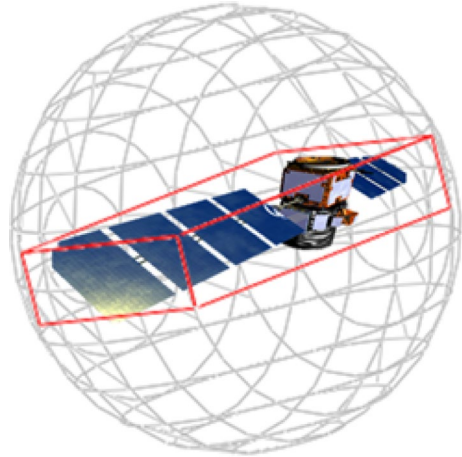
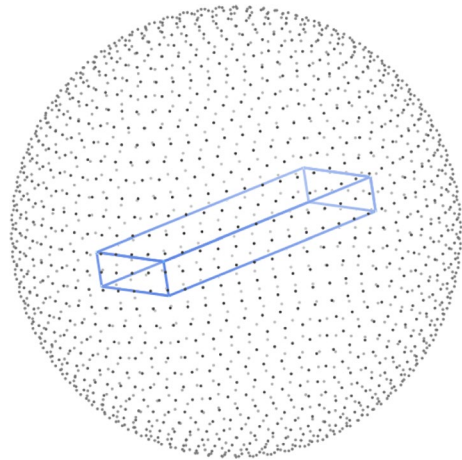


Fig. 10 Box surrounded by equally spaced viewing points



determine orientation, but results in an overestimated object volume and an over-inflated probability unless both satellites are actually spherical.

To produce more representative probabilities, Fig. 9 shows an enveloping rectangular box about a satellite of length (l), width (w), height (h) of 13 m, 4.3 m, and 1.6 m respectively. This representation more accurately portrays the actual collision threat by projecting a smaller area on to the conjunction encounter plane than a sphere [16], the downside is that the box's orientation must be known. Not knowing the orientation, uniformly spaced viewing angles (Fig. 10) provide a spectrum of values in ascending order for all projections (Fig. 11). The user then has the freedom to choose a suitable range of orientations. Point spacing of 0.007 steradians was deemed adequate to sufficiently analyze all projections of the rectangular box. As was shown in our previous work, even when choosing the maximum footprint possible, the resulting probability of the box will be less than that of the sphere.

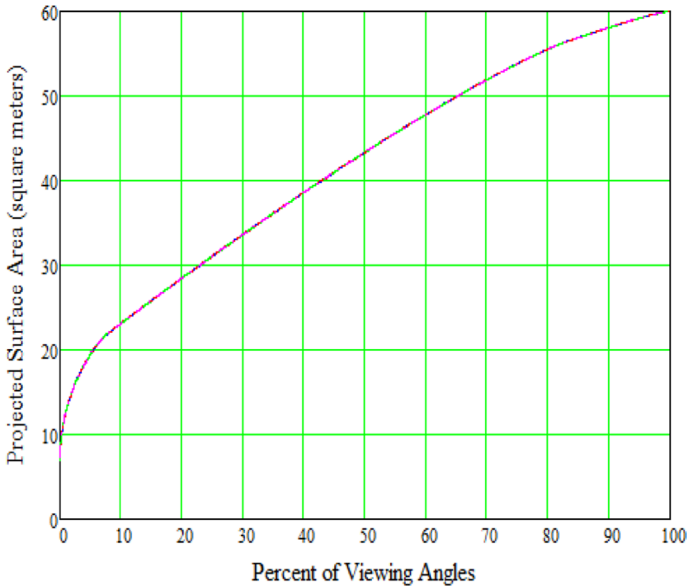


Fig. 11 Satellite area projections in ascending order

Figure 11 reveals that 80% of the viewing angles will observe a surface area at or below 56 m^2 , 50% below 44 m^2 , and so on. The associated radii for representative circles in the encounter plane are computed using a method similar to Chan's Method of Equivalent Cross-Sectional Area (MECSA) [17]. Unlike Xie and Chan's approach, the rectangular dimensions and orientation are redefined in the encounter plane rather than converting to a circle, thus simplifying the integrable region. The resulting radius distribution is shown in Fig. 12. Figures 10 and 11 show the box's largest projected area is 60 m^2 which will produce a circle of equivalent area with radius of 4.37 m.

An encapsulating sphere that touches the box's corners has a radius of 6.89 m with a projected area of 149.3 m^2 regardless of viewing angle. In the encounter plane, its projected circle will envelop the largest possible projected area of the box plus an additional 89.3 m^2 of density space. Thus, for the same centroid, the box's smaller footprint will produce a lower and more reasonable probability. This holds true for all cases because the encapsulating circle will always contain more probability density space than a box's projected maximum area.

The above process is applied to each conjuncting satellite's dimensions to produce its projected areas/radii. The minimum, maximum, and/or user-choice percentages of the box are used to establish their respective radii. When modeling an encapsulating sphere, its radius is used instead. Summing the radii for both objects determines the combined hardbody radii (CHBRs). In addition to representation as a circle, Ref. [18] also describes and demonstrates the use of squares and rectangles; its latter case is given below for analysis.

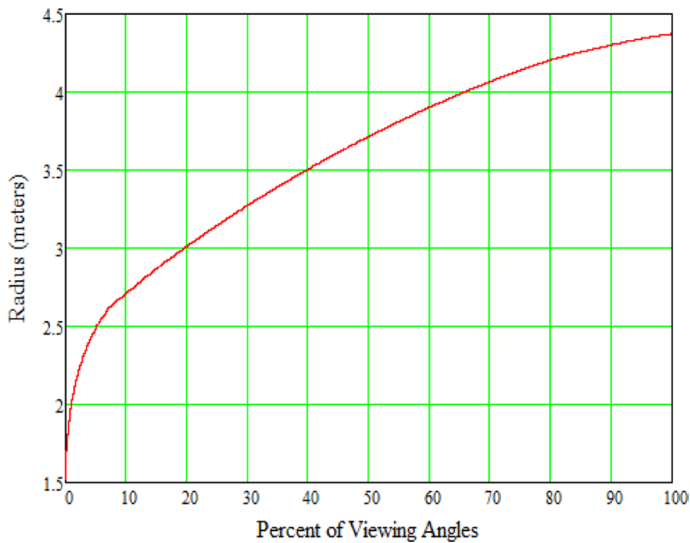


Fig. 12 Radii of satellite's area projections

US data predicted a close approach between the Infrared Astronomical Satellite (IRAS, NORAD ID 13777) satellite and the Gravity Gradient Stabilization Experiment (GGSE-4, NORAD ID 02828), forecast to occur on January 29, 2020, 23:39 GMT at roughly 900 km altitude. Both satellites were inoperable and therefore incapable of maneuvering. Progressive conjunction information from the 18th SDS repeatedly showed a miss distance under 20 m. Fortunately, the collision did not occur.

IRAS's box dimensions [3.6 m, 3.6 m, 2.05 m] and GGSE-4's dimensions [18 m, 0.7 m, 0.6 m] were used along with orbital data to produce Figs. 13 and 14 below. GGSE-4's encapsulating sphere was quite large due to its long protruding boom. This made it a good candidate to compare and contrast with the box's equivalent area representations.

Each object's maximum and minimum projections, as shown in Figs. 13 and 14, reveal that the satellites' equivalent projected areas produce considerably lower probabilities than encapsulation by eliminating density space. The values for the projected square and MECSA circle are so close that the lines somewhat overlap. GGSE-4's elongated shape causes a large difference between maximum and minimum projected areas, resulting in a large range of associated P_c values. More details about the various shapes (MECSA circle, square, rectangle) can be found in Ref. [15].

As expected, the greatest reduction benefit is for those objects having elongated boxes due to the reduction in probability relative to an encapsulating sphere.

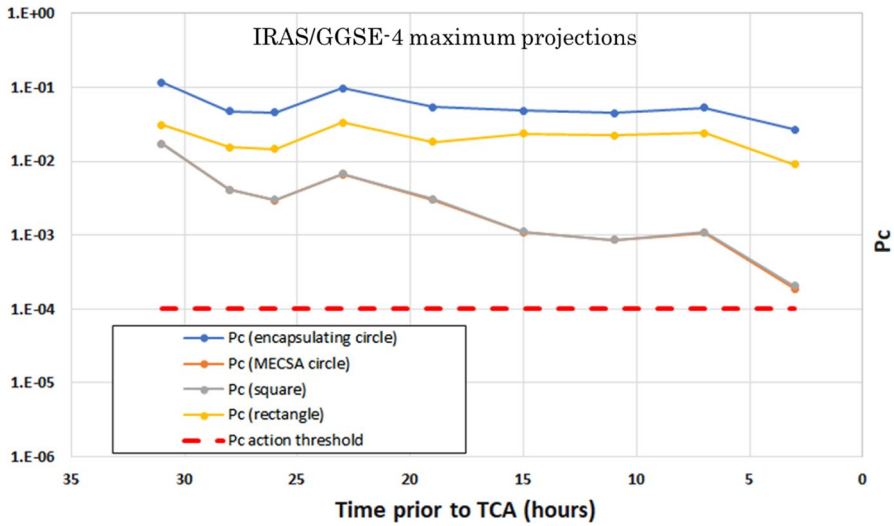


Fig. 13 IRAS/GGSE-4 maximum projections

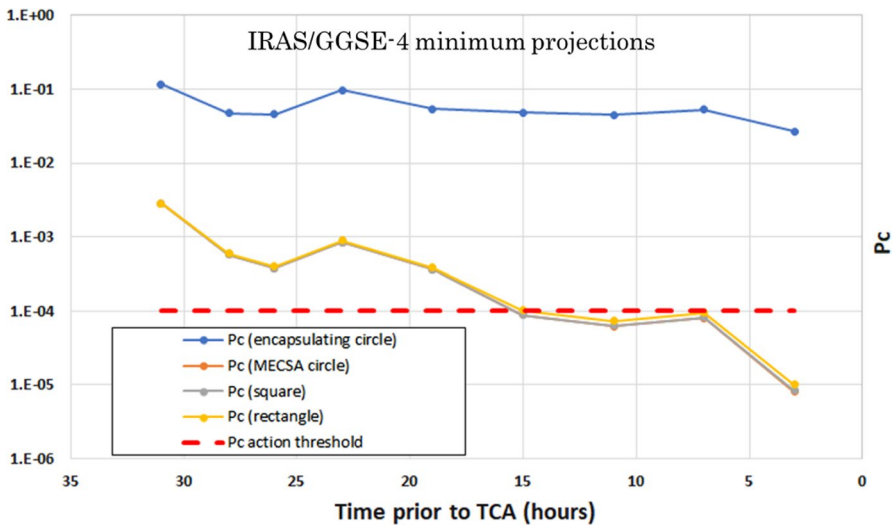


Fig. 14 IRAS/GGSE-4 minimum projections

4 Positional Accuracy

Positional accuracy, as defined by covariance, is needed for the probability calculation. The positional uncertainties are assumed to be zero-mean, Gaussian, uncorrelated, and constant for the short-duration encounter. The encounter region is defined when one object is within n standard deviations ($n\sigma$) of the combined

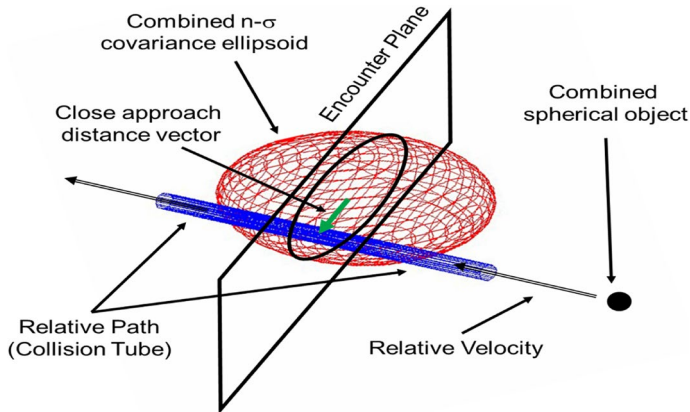


Fig. 15 Conjunction encounter visualization

covariance ellipsoid. This user-defined, three-dimensional, $n\sigma$ shell is centered on the primary object; n is typically in the range of 3 to 8 to accommodate conjunction possibilities ranging from 97.070911 to 99.999999%.

The assumptions allow the two objects' covariances to be summed, forming one, large, combined, covariance ellipsoid that is centered at the primary object. The secondary object passes quickly through this ellipsoid creating a cylindrical path that is characteristically called a collision tube. A physical overlap occurs if the secondary sphere comes within a distance equal to the sum of the two radii. Thus, a condition for collision is recognized. The probability of collision is obtained by evaluating the integral of a three-dimensional probability density function (pdf) within this long cylinder. Dimensional reduction is achieved by evaluating the collision tube's projection on a plane perpendicular to the relative velocity vector at closest approach. This becomes the encounter plane as illustrated in Figs. 15, 16.

As the positional accuracy varies, so does the probability. If the mean miss distance is greater than the combined object radius and the positional accuracy is nearly perfect (miniscule uncertainty), then probability will be close to zero. Likewise, if the positional uncertainty is enormously large, then probability will be close to zero. A maximum probability will exist between these two extremes as shown in the notional figure below. The region of increasing covariance beyond the maximum is called the dilution region. The curve shown is for a single, notional, miss distance. As shown in a subsequent section, different distances will alter the curve's shape but there will always be a maximum (Fig. 17).

When using probability as a decision metric, the relationship between miss distance d and absolute maximum probability P_{max} for spherical objects can be approximated if the combined object radius r and covariance aspect ratio AR are known [19]. AR is the ratio of the covariance major axis to its minor axis in the encounter plane. For this analysis, P_{max} occurs when the combined object's center lies on the major axis. The relational equation for linear relative motion is reasonably approximated by the analytical expression

Fig. 16 Encounter plane depiction

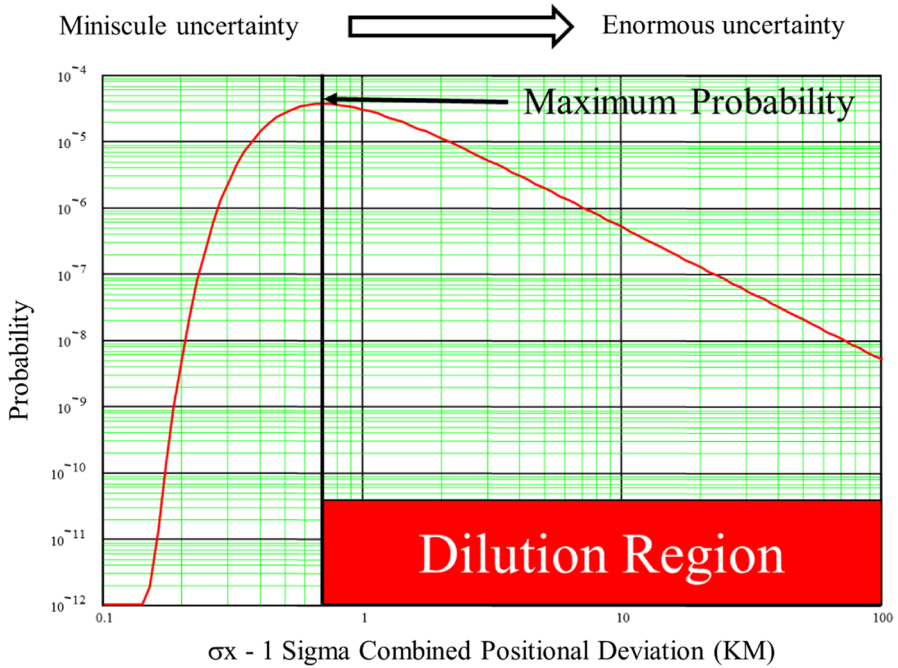
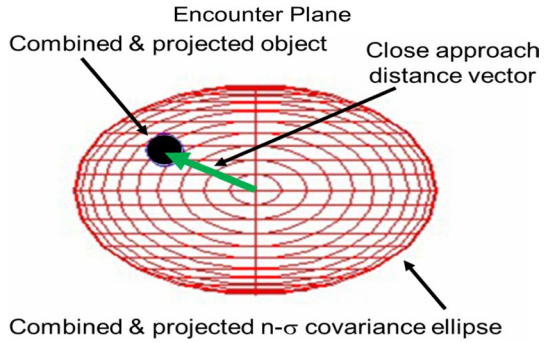


Fig. 17 Characteristic probability curve when varying uncertainty

$$P_{max} \cong \left(\frac{\alpha}{1 + \alpha} \right) \left(\frac{1}{1 + \alpha} \right)^{\frac{1}{\alpha}} \tag{1}$$

where α is

$$\alpha = \frac{r^2 AR}{d^2} \quad (AR \geq 1) \tag{2}$$

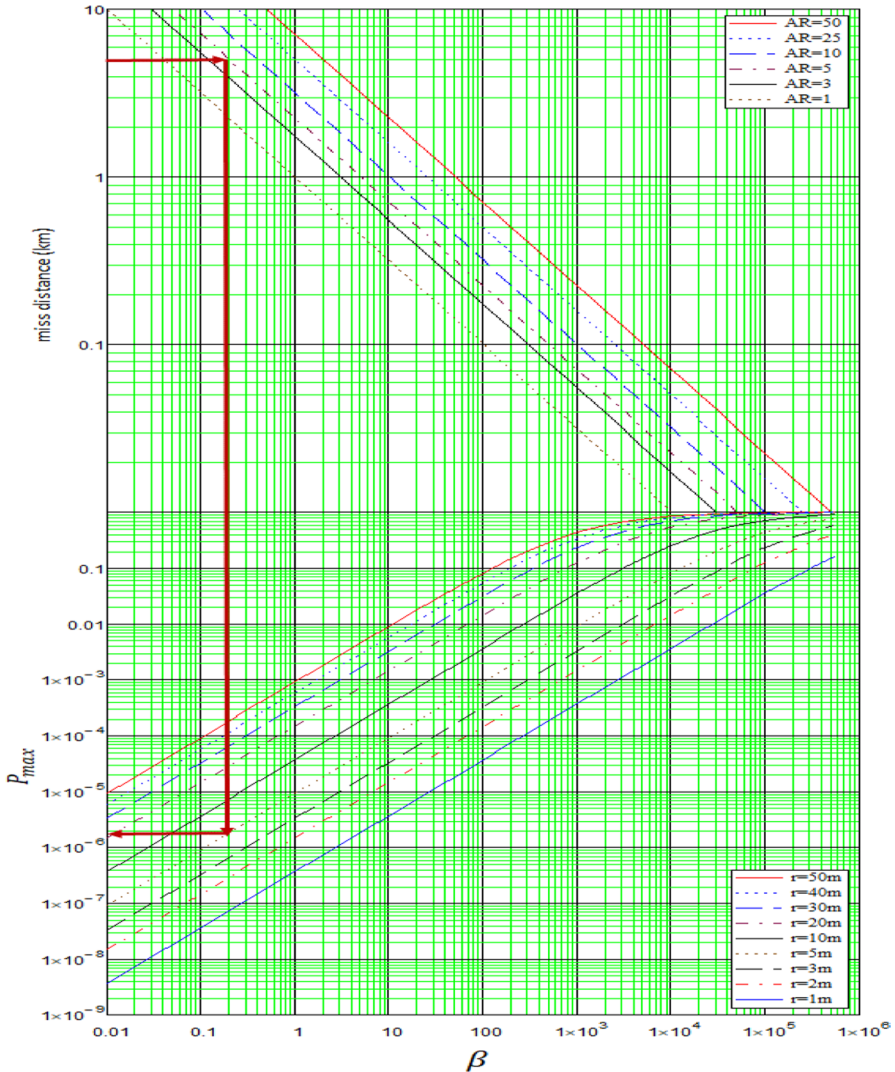


Fig. 18 Linked nomograms to determine P_{max} from r , d , and AR

Figure 18 linked nomograms to determine P_{max} from r , d , and AR shows the corresponding nomogram where β is an intermediate parameter that links two charts together.

The major-axis standard deviation σ_{major} associated with P_{max} at TCA is found through the equation

$$\sigma_{major}(TCA) = \sqrt{\frac{-\eta}{2 \cdot \ln\left(\frac{d^2}{d^2 + \eta}\right)}} \quad (AR \geq 1) \tag{3}$$

where η is

$$\eta = AR \cdot r^2 \tag{4}$$

A combined object radius r of 5 m, coupled with a combined covariance aspect ratio AR of 5 in the encounter plane and a miss distance d of 5 km, results in a P_{max} value of 1.84×10^{-6} . As shown in the Fig. 19 nomogram, the corresponding major-axis combined standard deviation σ_{major} is 3.5 km; its actual computed value is 3.535538 km. This standard deviation is associated with TCA and not orbit epoch. Although Eq. 1 is independent of orbit regime, covariance propagation from TCA is not; such dependence will affect the covariance at epoch. Knowing that orbit propagation causes the covariance to grow, it is necessary to work backwards to orbit epoch to determine the appropriate accuracy requirement that ensures the probability calculation does not occur in the dilution region. As the nomogram reveals, accuracy cannot be reduced to a single number; it is dependent on the combined object radius, combined covariance aspect ratio, and miss distance at TCA.

Table 6 provides required accuracies associated with common conjunction screening values, produced using the exact relationships and equations. Note that for a typical Low Earth Orbit (LEO) Combined Hard Body Radius (CHBR) of 1 m and an operator’s P_C threshold of five in ten thousand ($P_{max} = 5.E-04$), the allowable major eigenvalue’s (individual σ_{major}) corresponding one-sigma accuracy in the encounter plane should be no greater than 24 m (highlighted); for $AR=3$ the major axis should be no greater than 72 (3×24) meters. In Geosynchronous Earth Orbit (GEO), a typically larger spacecraft ($CHBR = 5$ m) might yield an allowable one-sigma accuracy of no greater than 117 m (highlighted). These are very demanding requirements. The table also shows the combined allowable major eigenvalue’s (combined σ_{major}) that would result from summing the individual covariances.

While the STCM Data Fusion Experiment [20] only considered 17 spacecraft, it is believed that the results are indicative of the accuracies one could expect operationally. For this limited sample size of spacecraft, the median percentile accuracy for GEO spacecraft when propagated for one day after orbit determination epoch ranged between three and five km for TLEs and one to three km for SP. For LEO spacecraft, accuracies ranged from 600 to 900 m for TLEs and 120 to 150 m for SP.

From Fig. 19 it is apparent that σ_{major} is heavily dependent on d for most cases, almost to the exclusion of r or AR . Realizing this, a zero-order approximation $\tilde{\sigma}_{major}$ is simply

$$\tilde{\sigma}_{major}(TCA) = \frac{d}{\sqrt{2}} \quad (r \ll d, AR < 50) \tag{5}$$

The approximate value $\tilde{\sigma}_{major}$ becomes 3.535534 km, closely matching the previous value. Attributing equal uncertainty to both primary and secondary objects yields half the miss distance at TCA.

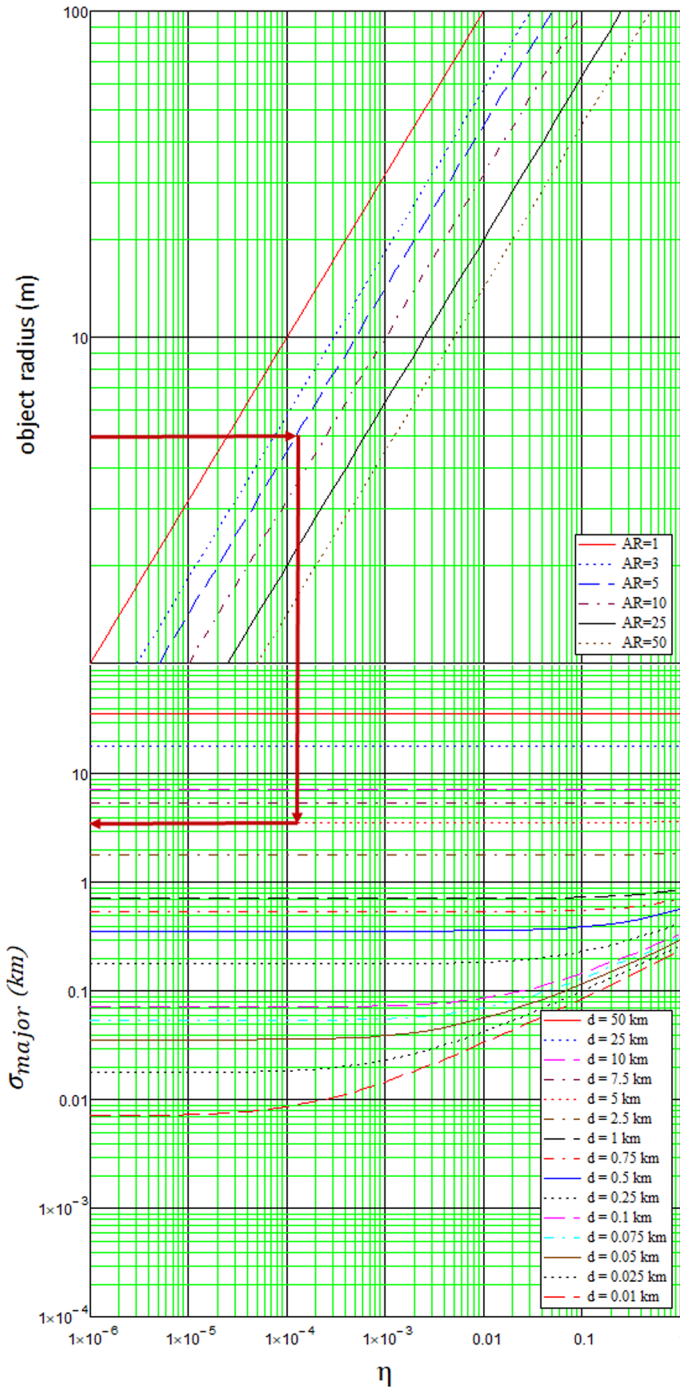


Fig. 19 Nomogram to determine σ_{major} from r , d , and AR

Table 6 Maximum allowable one-sigma error ellipsoid dispersion for assorted combinations of maximum probability and CHBR for aspect ratio AR=3

P_{max}	CHBR (m)	AR	distance (m)	combined σ_{major} (m)	individual σ_{major} (m)
1.E-04	0.5	3	53	37	26
1.E-04	1	3	105	74	53
1.E-04	1.5	3	158	111	79
1.E-04	5	3	525	371	263
1.E-04	10	3	1050	743	525
1.E-04	20	3	2101	1486	1051
1.E-04	50	3	5252	3714	2624
5.E-04	0.5	3	24	17	12
5.E-04	1	3	47	33	24
5.E-04	1.5	3	70	50	35
5.E-04	5	3	235	166	117
5.E-04	10	3	470	332	235
5.E-04	20	3	939	665	470
5.E-04	50	3	2348	1661	1174
1.E-03	0.5	3	17	12	8
1.E-03	1	3	33	24	17
1.E-03	1.5	3	50	35	25
1.E-03	5	3	166	117	83
1.E-03	10	3	332	235	166
1.E-03	20	3	664	470	332
1.E-03	50	3	1659	1174	830

$$\sigma_{primary}(TCA) = \sigma_{secondary}(TCA) \cong \frac{d}{2} \tag{6}$$

From the above equation, one can estimate accuracy requirements for each satellite at the TCA. In terms of determining the required accuracy for SSA positional information at orbit determination (OD), there are a variety of ways to account for the error growth expected to occur between the OD and the event time of interest (e.g., time of closest approach or TCA). Ideally, one would propagate the error covariances, accounting for error growth due to process noise. Different force models and altitudes will produce different accuracies. Alternatively, there are some rules-of-thumb which can be used to estimate the error growth. To illustrate, consider the force models associated with SGP4 at an altitude of 600 km. For an epoch one day prior to TCA, the required accuracy would be approximately $\frac{d}{4.72}$. Two days prior would necessitate an accuracy of $\frac{d}{7.5}$. An accuracy of $\frac{d}{10.2}$ would be needed 3 days prior [21, 22].

To assess miss distance along a single axial component, the encounter plane’s covariance ellipse is constructed such that the combined object contains all the probability mass associated with its minor axis [1]. This componentized distance reduces the problem to a single-dimension analysis along the major axis. The componentized maximum probability P_{max_1d} is

Table 7 Probability density percentages versus $n\sigma$

Dimension	1σ (%)	2σ (%)	3σ (%)	4σ (%)	5σ (%)	6σ (%)
1D	68.269	95.450	99.730	99.994	99.9999427	99.9999998
2D	39.347	86.467	98.889	99.967	99.9996274	99.9999985
3D	19.875	73.854	97.071	99.887	99.9984561	99.9999925

$$P_{max_1d} = \frac{1}{2} \left(\operatorname{erf} \left[\frac{1}{2} \left(\frac{r}{d} + 1 \right) \frac{\sqrt{2}}{\sigma_{1d}(TCA)} \right] + \operatorname{erf} \left[\frac{1}{2} \left(\frac{r}{d} - 1 \right) \frac{\sqrt{2}}{\sigma_{1d}(TCA)} \right] \right) \quad (7)$$

with an associated component axis standard deviation of

$$\sigma_{1d}(TCA) = \sqrt{\frac{2rd}{\ln\left(\frac{d+r}{d-r}\right)}} \quad (8)$$

where d is the miss distance along the component axis.

The dependence on proper covariance is essential. One must ensure that the covariance used in these computations is positive-definite, be it from CDM, owner/operator, or other source. If not positive-definite, then covariance rejection or rectification must be considered.

5 Mahalanobis Distance Screening

A bridge linking Cartesian and Mahalanobis spaces is found from the combined, positional, 3×3 covariance matrix C and relative position $[x \ y \ z]$. Mahalanobis distance d_{maha} is determined from the equation

$$d_{maha}^2 = [x \ y \ z] C^{-1} \begin{bmatrix} x \\ y \\ z \end{bmatrix} \quad (9)$$

where the three positional components represent the vector from the combined covariance center to the combined object’s center at TCA. If one wishes to consider r , the vector components can be adjusted to touch the combined object’s sphere closest to covariance center in the Mahalanobis space. This can be approximated by reducing the vector’s magnitude by r while maintaining its directionality.

Decision criteria is based on the object being inside ($d_{maha} < n$) or outside ($d_{maha} > n$) the covariance ellipsoid’s n -σ shell. Similarly, this approach can be dimensionally reduced to assess a single component for radial screening or dual-component, planar screening. Table 7 shows the probability density percentages contained within n -σ for various dimensions.

Mahalanobis distance is computationally less burdensome than the P_C calculation. Some choose solely to use this distance for maneuver consideration while some others use it to determine if a probability calculation is further warranted. As an example using the table below, the P_C calculation would not be needed if the probability threshold was 0.0005 and the two objects were 5σ apart. This is because the combined object could not possibly occupy enough density space to match or exceed the threshold.

6 Maneuver Frequency Dependencies

6.1 Various Criteria

There are a variety of criteria that operators use when determining if a maneuver is warranted. The three most common criteria are cartesian miss distance, componentized miss distance such as radial separation, and conjunction probability.

6.1.1 Distance-Based Criteria

When used appropriately, the action threshold for a miss distance-based screening criterion should conservatively encompass the combined positional knowledge accuracy for the two conjuncting objects at the TCA. This approach was listed as “Max Probability-based Cartesian miss distance” in Table 1. As has been demonstrated in many encounter rate characterization papers [9, 23–26], the inverse relationship between encounter frequency and the spherical radius for a miss distance metric indicated by kinetic gas theory’s “time between collisions” is a very good approximation of the number of times that a miss distance threshold is violated in a given time span when the background space population is fairly homogenous. Under these assumptions, one can approximate how the number of avoidance maneuvers might scale from a baseline encounter rate for a 100 m keep out sphere as a function of combined positional accuracy as shown in Fig. 20. The highlighted example corresponding to a combined positional accuracy of 7 km indicates that the operator would have to do five thousand times more maneuvers than an operator who had highly accurate data whose combined positional accuracy was one hundred meters.

The squared relationship regarding three-dimensional miss distance screening previously presented is based on the projection of a circle through the miss distance sphere normal to the encounter plane. The relationship works because for any encounter geometry, there is a circular encounter area being swept out in the relative velocity direction (i.e., normal to the encounter plane).

6.1.2 Componentized Miss Distance-Based Criteria

As presented in Sect. 2, operators may not trust certain components of the predicted miss distance vector at the TCA. Such mistrust may arise if the dominant propagation

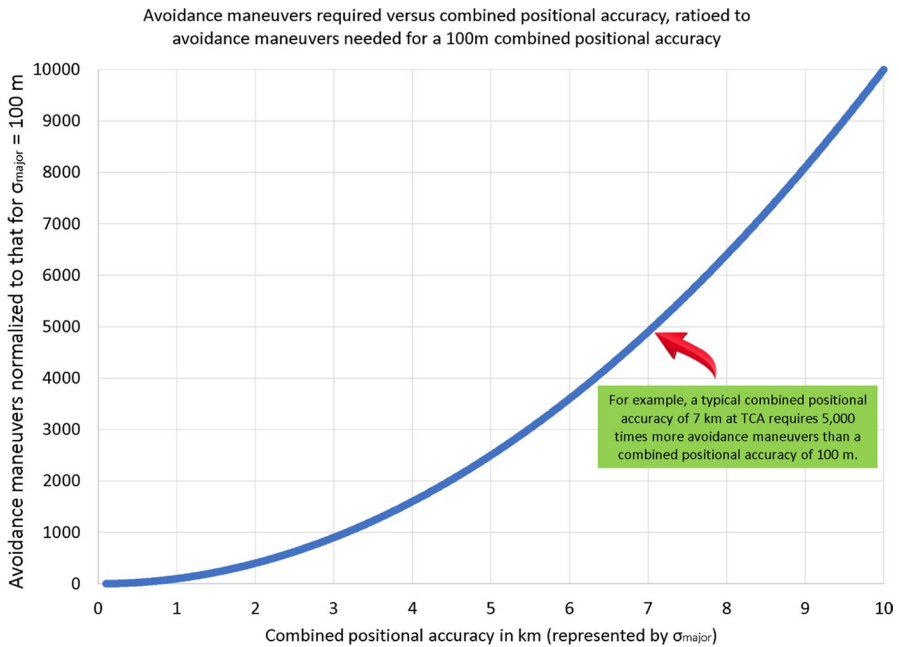


Fig. 20 Encounter rate increase as a function of combined positional accuracy for distance-based screening

errors in the orbit regime in question lead to errors in certain component(s), or if the type of SSA sensor being used to gather the orbit tracking observations has a known weakness that can lead to large errors in one or more error component(s) when propagated forward. For example, operators have been known to emphasize the radial miss distance component and ignore in-track in a high-drag environment.

If the selected miss distance component direction lies in (i.e., is parallel to) the encounter plane for typical encounters, then one may expect the encounter rate to vary linearly as this miss distance threshold is increased, because the screening process will admit more conjunctions proportional to that component. But if the chosen miss distance component tends to run normal to the typical encounter plane direction, then there will likely be little encounter rate dependency as that component's threshold is increased or decreased.

6.2 Probability-Based Criteria

In contrast to the distance-based screening threshold d -squared relationship discussed above, there is no direct general relationship between collision probability and the number of maneuvers required. As seen in Fig. 21 Representative depiction of P_c topology below, the P_c rate of change varies greatly depending on the miss distance and positional certainty. Whereas Fig. 17 Characteristic probability curve showed the effect on probability with positional accuracy variations and a specific

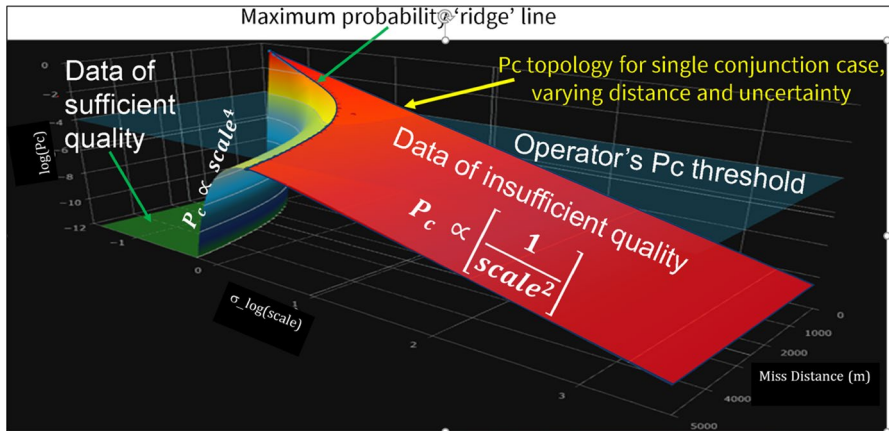


Fig. 21 Representative depiction of P_c topology

miss distance, Fig. 21 Representative depiction of P_c topology shows a topology where the miss distance is also varied. The figure’s horizontal axis shows the logarithmic scaling “ $\sigma_{\log}(\text{scale})$ ” of the combined covariance matrix to assess its impact on the P_c calculation. The depiction is unique to all the inputs affecting the probability calculation; each conjuncting pair will produce its own topology.

The dilution boundary is defined where the maximum probability ridge line has zero slope. As covariance scaling increases from this boundary, its quality is no longer considered sufficient; the slope of the topology asymptotically approaches a squared relationship which is called the dilution region. On the other side of the ridge line the data quality is deemed sufficient and is called the confidence region; the topological slope is asymptotically defined by a quartic relationship.

7 SSA Data Fusion Experiments

In a recent demonstration of SSA data fusion involving 14 organizations [20], it was found that comprehensive data fusion that incorporated data from government, commercial spacecraft operators, commercial SSA data and information providers and academia resulted in substantial accuracy improvements in all orbital regimes. In that demonstration, a single go/no-go criteria (collision probability) and accompanying threshold (one in ten thousand, as is commonly used by several operators particularly in LEO) was input to the processes of Sect. 4 to determine what positional accuracy is required to achieve such a collision probability.

Significantly, when the resultant required relative positional accuracy was allocated to both conjuncting objects equally, it was determined that the accuracy of the SSA products being used in the collision probability assessment process were generally insufficient to support the metric and corresponding threshold being operationally used to ensure flight safety. Said succinctly, the SSA data quality did not support the way it was being used. Three ways to address this troubling finding are: (1) use

data fusion and invite data exchange necessary to achieve the required accuracy; (2) reconsider the go/no-go metrics being used to determine risk; and (3) reevaluate the threshold(s) being employed to ensure that existing positional data accuracies are harmonized with the thresholds and metrics the operator uses.

8 Conclusion

Perhaps one of the biggest shortcomings in our use of SSA data today is the general lack of effort to assure ourselves that SSA data is sufficiently accurate to support the purpose intended. In this paper, many of the collision avoidance maneuver Go/No-Go criteria available to the operator are listed. In summary, twenty spacecraft operators who collectively operate almost 600 spacecraft spanning all orbit regimes, revealed the diverse/disparate metrics and corresponding thresholds that they use operationally.

The survey highlighted a lack of consensus among operators on which metrics to monitor and which thresholds to use as Go/No-Go criteria and collision avoidance maneuver targets. This is because different operators have different concepts of operations and different constraints in terms of staffing, spacecraft performances, and resources (some rely on commercial systems that refine solutions provided by institutional free-of-charge services). While all operators in LEO monitor probability of collision to assess the risk of a conjunction, many GEO operators still rely solely on geometrical considerations (mainly because the CDMs provided by the 18th SDS have not historically included P_C).

When miss distance-based screening thresholds are set to encompass the maximum errors for the two conjuncting objects, the impact of using poor-quality SSA data is that the number of encounters increases as the square of the SSA data error profile. Operators then have a very difficult time knowing which potential collisions require mitigation probability-based screening thresholds demand accurate orbits accompanied by realistic covariance data. Many of the probability metrics and thresholds employed by spacecraft operators today require more accurate SSA data than the operators have available to them, greatly diminishing the value of today's conjunction assessment and collision avoidance processes.

Finally, the relationships were examined to map these metrics and thresholds back to typical accuracy requirements to ensure that collision avoidance processes produce meaningful, effective results. As was demonstrated in a recent STCM data fusion campaign, such accuracy requirements are often not met by legacy flight safety systems. Collaborative sharing of authoritative data (ephemerides, maneuver plans, observations, object dimensions and mass, attitude flight rules) and large-scale data fusion offer the best opportunities to ensure that actionable SSA products are generated that are of sufficient accuracy to be used by spacecraft operators for their adopted Go/No-Go criteria and thresholds.

Future work will involve surveying non-SDA members to develop a better understanding of Go/No-Go decisions and the reasoning behind those metrics. Additionally, focus on the quality of the CDMs provided to the operators will be examined.

Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest in the publication of this paper.

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