Evaluation of Screening Volumes Used in Conjunction Assessment

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ABSTRACT

One of the first steps in the Conjunction Assessment (CA) process is the use of Screening Volumes (SVs) to filter out conjunctions that occur at long distance and are unlikely to be high-risk events. This step reduces the total number of conjunctions for which more complex risk calculations must be applied and reduces computational cost, but too small an SV will risk missing high-risk events. Thus, it is worthwhile to consider the optimal SV size to minimize total conjunctions processed without missing high-risk events.

This study sought to determine the optimal SV sizing to balance these two objectives. Historical space object catalogs from 2020-2024 were used to generate simulated conjunction data and a range of SV dimensions were tested against this data. Each tested SV was evaluated based on the total conjunctions processed and the rate of high-risk event detection. This study focused on two sets of SV dimensions: the SVs currently employed by NASA Conjunction Assessment Risk Analysis (CARA) program and SVs proposed by the Office of Space Commerce for use in their Traffic Coordination System for Space (TraCSS.) It was found that NASA could decrease their current SV dimensions and significantly reduce the number of conjunctions processed, while the smaller TraCSS SVs are already very close to optimal.

1. INTRODUCTION

The primary objective of Conjunction Assessment (CA) in spacecraft operations is to minimize the risk of on-orbit collisions. The CA process can be summarized in three steps [2, 4]:

1. Conjunction screening - The process of comparing trajectory data from a primary object against object trajectories in a secondary catalog and predicting when close approaches will occur,
2. Conjunction risk assessment - The determination of the probability that two Space Objects (SOs) will collide, generally via the probability of collision (P_c) metric,
3. Conjunction mitigation - The action taken when risk exceeds an allowable threshold to reduce P_c to a tolerable level.

The risk assessment step must be performed for every detected conjunction and can be a computationally expensive process, involving uncertainty propagation and complex risk calculations. To reduce unnecessary processing of low-risk conjunctions, analysts only consider conjunctions in which the secondary object penetrates a certain volume centered around the primary object, also known as the Screening Volume (SV). This reduces the total number of Conjunction Data Messages (CDMs) produced by the initial screening which in turn reduces the overall computational burden of risk assessment. SVs are generally either ellipsoidal or box-shaped and can vary in size based on the dynamics of a given orbit - for instance, larger SVs are used in low-altitude orbits because atmospheric drag results in larger uncertainties.

SV sizes also influence the computational cost of the CA process, as smaller SVs will produce less CDMs to process at the risk of disregarding a high-risk event. This paper presents an evaluation of whether the SVs currently employed by the NASA Conjunction Assessment Risk Analysis (CARA) program could be reduced in size without compromising CARA's ability to detect high-risk conjunctions. If such reductions could be made, CARA would be better equipped to handle the ever-growing scale of the conjunction detection problem. In addition to analyzing the CARA SVs, this study will also evaluate the SVs being proposed by the Office of Space Commerce (OSC) in their Traffic Coordination System for Space (TraCSS.)

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2. BACKGROUND

2.1 Orbit Regime Definitions

The SV sizes currently used by NASA CARA and those being considered by OSC for use in TraCSS are listed in Tab. 1. The SVs proposed for use in TraCSS are currently in use by the Department of Defense and are documented in the Spaceflight Safety Handbook[1]. Dimensions are provided in a Radial, In-track, Cross-track (RIC) coordinate system.

Table 1: Orbit regime definitions RIC SV sizes

Regime	Perigee Altitude (km)	Eccentricity	NASA CARA SV Size (km)	TraCSS SV Size[1]
LEO-1	< 500	< 0.25	2 x 44 x 51	0.4 x 44 x 51
LEO-2	$500 - 750$	< 0.25	2 x 25 x 25	0.4 x 25 x 25
LEO-3	$750 - 1200$	< 0.25	2 x 25 x 25	0.4 x 12 x 12
LEO-4	$1200 - 2000$	< 0.25	2 x 25 x 25	0.4 x 2 x 2
HEO	< 2000	≥ 0.25	40 x 77 x 107	-
GEO/DS	-	< 0.25	40 x 40 x 40	10 x 10 x 10

The GEO/DS regime is defined as orbits with the following properties:

- 1,300 minutes $<$ Period $<$ 1,800 minutes,
- Eccentricity < 0.25,
- Inclination < 35 degrees.

The larger SV dimensions in the in-track/cross-track directions reflect the higher uncertainties inherent in these directions. The larger overall dimensions at the lower LEO altitudes also reflect the greater dynamic uncertainty due to atmospheric drag.

3. METHODOLOGY

This section outlines the methodology used to perform the SV evaluation. First, a set of test conjunctions are generated using historical catalog states. These conjunctions are used to test an array of different SV sizes based on how many CDMs are processed and how many high-risk events fall within the SV.

3.1 Data Generation

The SV size trade study was performed by using 4 years of historical satellite catalogs from 2020-2024 to perform simulated conjunction screenings. Conjunction data was generated by the SuperCOMBO[1] (Super Computation of Miss Between Orbits) analysis tool which propagates the space object catalog and detects close approaches between objects within user-defined thresholds. For this study, we screened a curated satellite set consisting of

- 135 primaries in LEO,
- 84 primaries in HEO,
- 1,900 primaries in Deep Space (DS)

against the entire space object catalog. Fig. 1 shows the distribution of all LEO objects, which were selected to cover a range of altitudes and inclinations throughout each LEO sub-regime.

[1]SuperCOMBO is an application program in the Astrodynamics Support Workstation (ASW). It is based on the Air Force Space Command (AFSPC) Astrodynamics Standards program COMBO [7, 6, 5].

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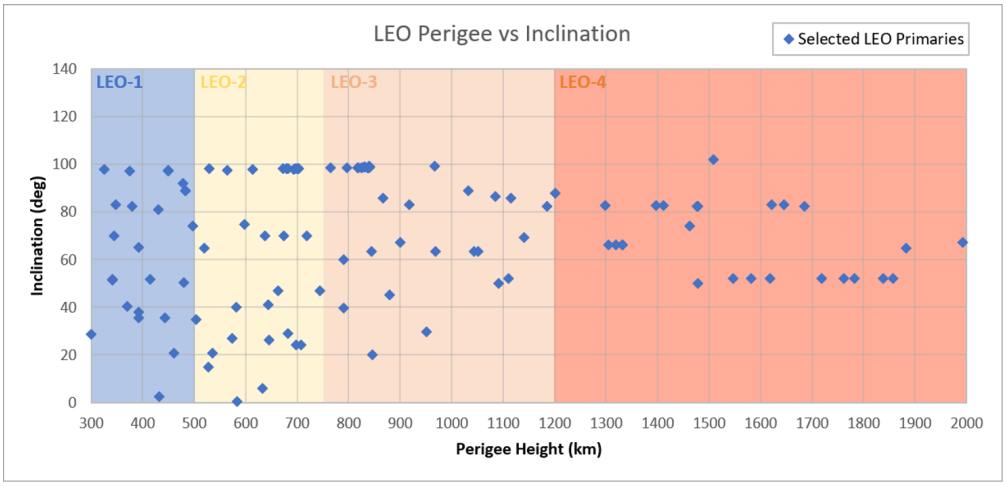

Fig. 1: Altitude and inclination for all primaries used in the LEO set.

Simulated screenings were performed once per day and screened for events up to 7 or 10 days (depending on orbit regime) in advance using screening volumes on the order of hundreds of kilometers in each direction. We used a lower screening frequency than CARA's standard of three per day to reduce computational costs. All conjunctions within a 250 x 250 x 250 km sphere were recorded to ensure that no potential high-risk events were missed and to allow for larger-than-nominal SVs to be considered. Finally, conjunctions across multiple screenings that have similar estimated Times of Closest Approach (TCA) and involve identical satellite IDs are associated with each other as corresponding to a single event. This produced a full list of events between all cataloged secondaries and our subset of test primaries.

The total numbers of conjunctions generated for each regime are listed in Tab. 2. These are the total numbers of CDMs generated with the expansive SVs and not necessarily reflective of actual numbers of CDMs currently processed by NASA CARA.

Table 2: CDMs generated by orbital regime

Regime	CDMs
LEO-1	405,262,915
LEO-2	624,924,500
LEO-3	652,959,605
LEO-4	82,461,454
LEO total	**1,765,608,474**
HEO	809,478,633
GEO/DS	138,790,804

3.2 High-Risk Event Definition

After recording all relevant conjunctions, the corresponding collision probabilities P_c were calculated using covariance data generated by the SuperCOMBO process. P_c values were generated using the P_c-multistep algorithm which applies the relatively simple 2D-P_c algorithm by default, and uses higher-fidelity methods where necessary[3]. Assumptions about the Hard-Body Radius (HBR) values of primary objects were made, even though HBR data was available for many of the primaries being studied, in order to remove potential biases in the calculated P_c based on the sizes of the chosen primary objects and to provide a degree of conservatism. These assumptions differed based on the orbital regime being analyzed and will be stated in the relevant results sections. HBR values for all cataloged secondaries used estimated values based on Radar Cross-Section (RCS) data when available, and a default value of 1.5 meters otherwise.

As stated previously, a single event generally produces conjunctions across multiple screenings. The estimated collision probability will change from one screening to the next as the state catalogs incorporate newer tracking data and the propagation time to TCA decreases, producing a sequence of P_c values rather than a single value for each event.

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P_c generally evolves as screenings get closer to the estimated TCA and P_c is calculated with smaller covariance matrices due to the shorter propagation times. Events that yield a high P_c multiple days out from TCA may later produce lower risk values as more tracking data is processed. For this study, we were concerned with events that are detectable during the screening period and register as high-risk shortly before TCA. We define these *actionable red* events as events which:

- Register as red ($P_c \geq 10^{-4}$) during the maneuver commit window spanning 0.5-1.5 days before TCA,
- Register as yellow ($10^{-4} > P_c \geq 10^{-7}$) or red during the detection window spanning 2/3/4-7 days before TCA.

Note that multiple timeframes are provided for the detection timeframe as this study will consider SV size considerations for multiple detection windows. The maneuver commit window of 0.5-1.5 days before TCA was chosen as a broadly representative timeframe, and varies from mission to mission in practice.

These criteria exclude events that only become red after the maneuver commit window (*late-notice* red events) or become red during the maneuver commit window but never register as yellow or higher before the window, effectively going undetected. While undetectable/late-notice events are issues within CA, they are not problems that are remediable through SV size adjustments are are thus not considered in this trade study.

From these criteria, we obtained a set of detectable red events over four years with which to test the event detection rates of various SV sizes. Note that while the vast majority of close approaches do not produce a high-risk event of any sort, they are still a part of the overall loading to the CA process and are still considered when evaluating SV efficiency.

3.3 Screening Volume Analysis

Finally, these conjunction data are used to evaluate a range of SV dimensions on performance and efficiency. Efficiency is measured by the total number of conjunctions detected by the SV, as each in-SV conjunction produces a CDM to undergo risk analysis. Performance is evaluated via red event capture rate, which is the ratio of red events detected by the SV to the total number of red events that occur in the data, and is ideally equal to 100%. These measures are computed for every set of RIC dimensions in a 3D grid and are used to visualize the space of SV dimensions that achieve a desired performance metric through capture rate frontier plots introduced by Hejduk and Pachura [4]. Fig. 2 displays an example frontier plot to outline how results are presented. The in-track direction is the out-of-plane direction as this dimension generally has the greatest estimated uncertainty and is treated as the optimization direction. Colored regions indicate the necessary in-track dimension needed to achieve the desired capture rate for a given R/C combination, while white regions indicate that no tested in-track dimension can achieve the desired performance threshold for that combination. For reference, a red 'X' symbol is used to mark the nominal radial/cross-track dimension.

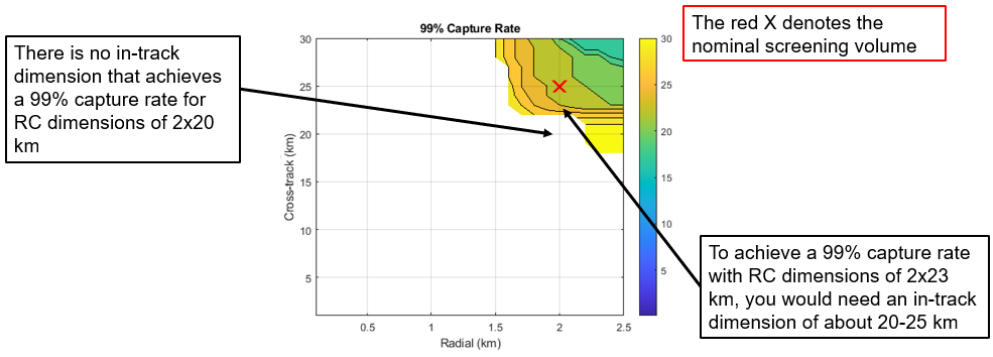

Fig. 2: An example of the capture rate frontier plots used to visualize performance results. In this example, the frontier corresponds to a 99% capture rate.

We also provide plots of the computational gains across the efficient frontier, an example of which is shown in fig. 3. Colored areas indicate the ratio of CDMs processed by the corresponding RIC dimensions from the efficient frontier,

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while white areas indicate dimensions that are off the frontier. The absolute minimum CDM ratio is denoted with a blue 'X', though in practice it is often desirable to use a slightly less efficient SV to provide robustness. Note that the CDM ratio at the nominal SV location denoted by the red 'X' may not necessarily be equal to 1 because the plotted CDM ratio corresponds to the frontier in-track dimension, not the nominal in-track dimension.

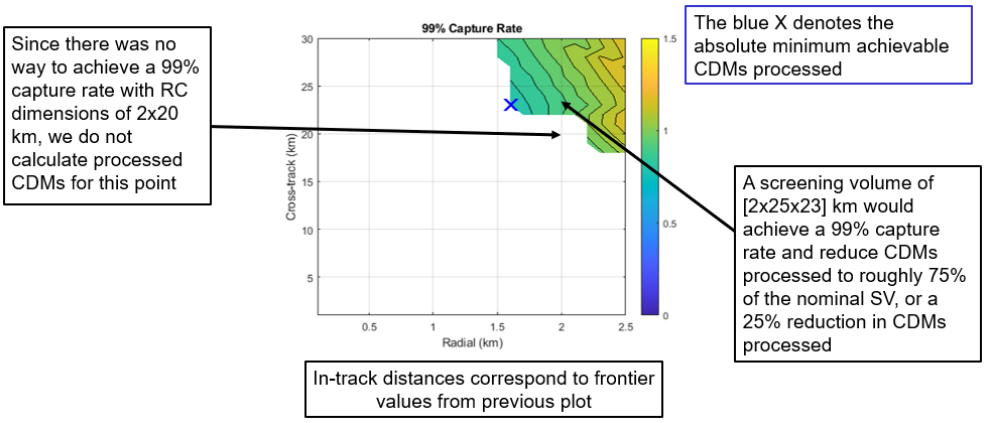

Fig. 3: An example of the CDMs processed contour plots used to visualize computational load

3.4 HBR Inflation

Some primaries were selected for their orbital parameters, and their sizes are smaller than typical operational spacecraft. To prevent computed risk values from being biased by the presence of smaller objects, HBR values for primary objects in LEO were inflated to 14.5 meters, the 99th percentile value among all space objects. This in turn inflated computed P_c values which yielded a larger set of actionable red events for testing and also provided a degree of conservatism as the scenario under which the SVs are being evaluated is more "difficult" than the actual space environment.

Some of the conjunctions for which the HBR inflation elevated their computed risk into the actionable red range occurred over relatively long distances, comparable to current nominal SVs or even further. While such events are rare, their presence makes it very difficult to maintain a 100% capture rate under any noteworthy reduction in SV dimensions. This effect is illustrated in fig. 4. With inflated HBR values, there are a small number of high-risk conjunctions that occur at or beyond the current nominal SV boundaries, which makes it impossible to apply any reduction to SV dimensions without seeing a performance decrease. If we re-adjust P_c to use actual or estimated HBR values for each primary rather than the 14.5 meter value used in this study, these events drop below the threshold value of 10^{-4} and would no longer count against the detection rate of tested SVs.

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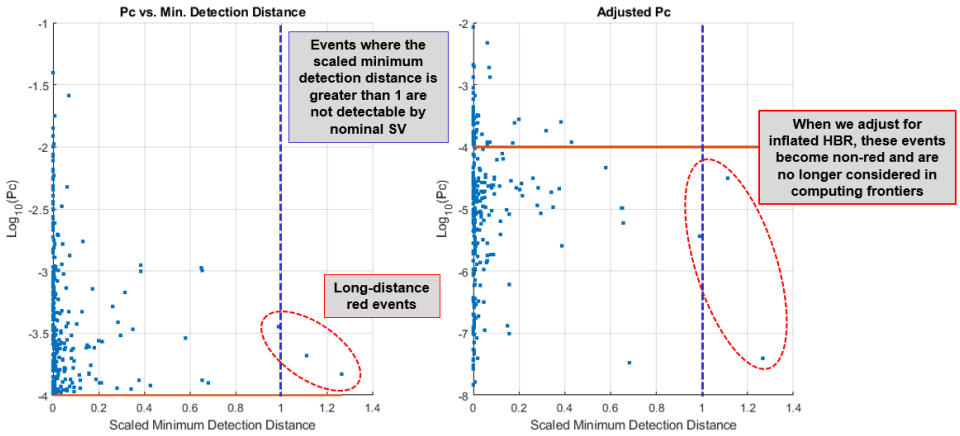

Fig. 4: Effects of using HBR inflation on conjunction Pc values. The left plot shows calculated P_c values using inflated HBR values while the right plot shows calculated P_c values adjusted to reflect actual or estimated HBR values. Scaled minimum detection distance is the length of the Distance of Closest Approach (DCA) vector scaled by the nominal SV dimensions, so any conjunction with a scaled minimum detection distance greater than 1 lies outside of the nominal SV ellipsoid and is undetectable by the nominal SV.

While using actual or estimated HBR values would remove these outlier events, it would also significantly reduce our set of detectable red events. It is possible that the impact of outliers could be overcome via more data generation (More primaries, more years, 3 simulated screenings per day, etc.) but this is computationally expensive and it is not guaranteed that the proportion of relative outliers will trend downward. We consider HBR inflation a necessary element to generate a sufficiently large set of red events in a computationally feasible timeframe. We observed roughly 3-4 long-distance red events in each LEO regime. Since most LEO regimes have a sample size of 150-200, a 98% capture rate would effectively be a 100% capture rate after discounting these outliers. Thus, we will base our conclusions on 98% capture rates frontiers.

4. RESULTS

4.1 NASA CARA Screening Volumes

We analyzed SVs currently used by NASA CARA to determine if reductions to SV sizes could yield lower numbers of CDMs processed without affecting current performance. For each regime, we present an array of frontier plots corresponding to a combination of detection-commit window and desired performance level. For the NASA CARA SVs, we considered detection windows of 7-2/3/4 days and performance metrics of 0 events missed, 1 event missed, 99%, and 98% capture rate. Note that for sample sizes under 200 events, the frontiers for 1 event missed and 99% will be identical.

4.1.1 LEO-1

Fig. 5 shows the performance frontiers for the LEO-1 SV study. Corresponding ratios of CDMs processed are shown in fig. 6. While shorter windows give analysts less time to detect events and may be considered the more difficult use case, longer windows encompass more detectable red events and can produce more restrictive frontiers if some of these additional events occur at long distances.

Results show that while the current nominal LEO-1 SV is off of the 100% performance frontier, it is will within the 98% performance frontier with room for reductions. As discussed previously, HBR inflation artificially induces high risk in certain long-distance conjunctions, and recommendations should be formulated using the 98% frontier. Plots in fig. 6 show that CDM reductions are mainly driven by reductions to the radial dimension, and that CDMs processed could be reduced by roughly 50% if the SVs are brought all the way to the frontier edge.

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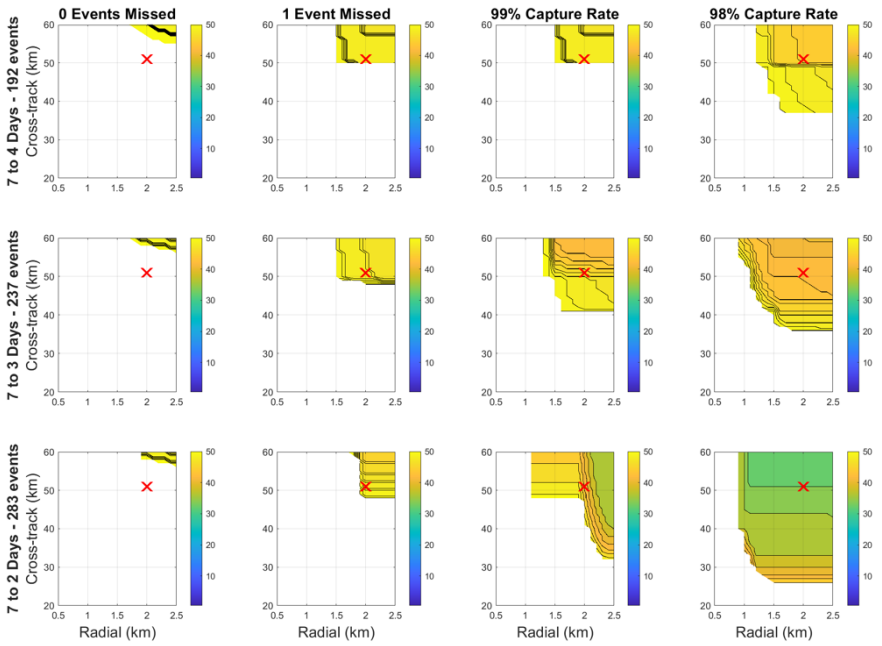

Fig. 5: Performance frontiers for the LEO-1 SV.

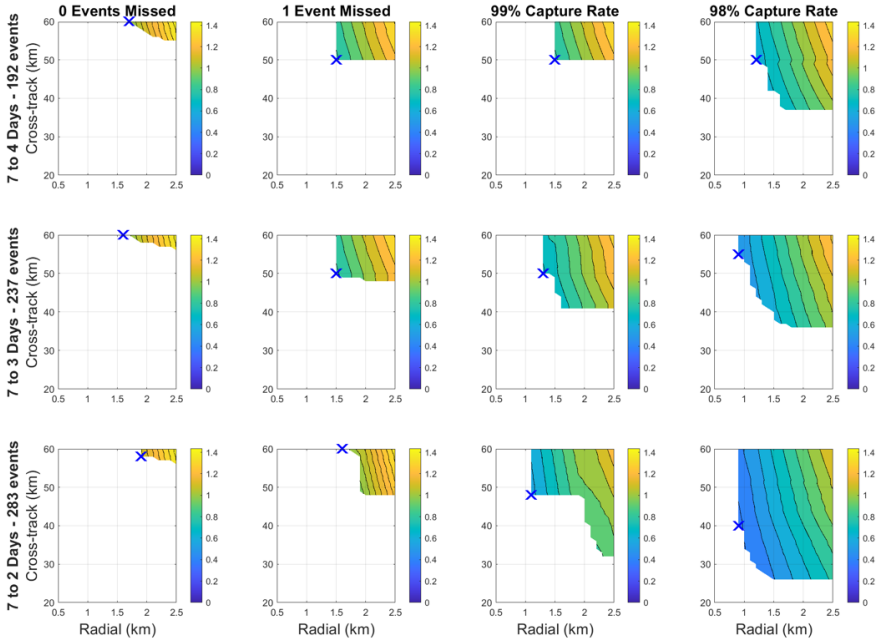

Fig. 6: Ratios of CDMs processed by frontier SVs to CDMs processed by the nominal LEO-1 SV

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4.1.2 LEO-2

Fig. 7 shows the performance frontiers for the LEO-2 SV study. Corresponding ratios of CDMs processed are shown in fig. 8. The 98% performance frontier similarly shows that there is significant room to consider reductions to the LEO-2 SV. CDM ratio plots again show that reductions in the radial direction will provide the most computations gains.

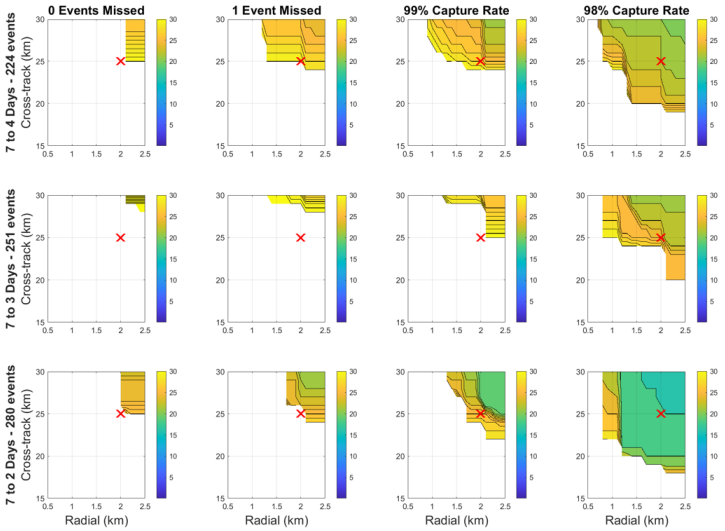

Fig. 7: Performance frontiers for the LEO-2 SV.

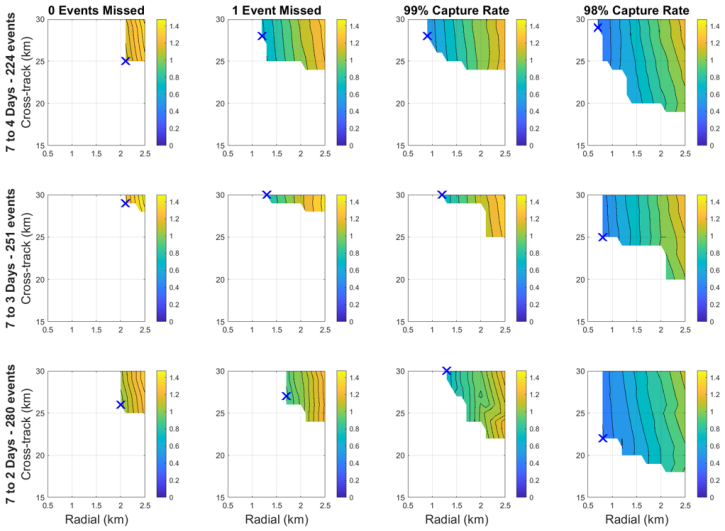

Fig. 8: Ratios of CDMs processed by frontier SVs to CDMs processed by the nominal LEO-2 SV

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4.1.3 LEO-3

Fig. 9 shows the performance frontiers for the LEO-3 SV study. Corresponding ratios of CDMs processed are shown in fig. 10. The 98% performance frontier plots and corresponding CDM ratio plots suggest a similar course of action as in LEO-1/2.

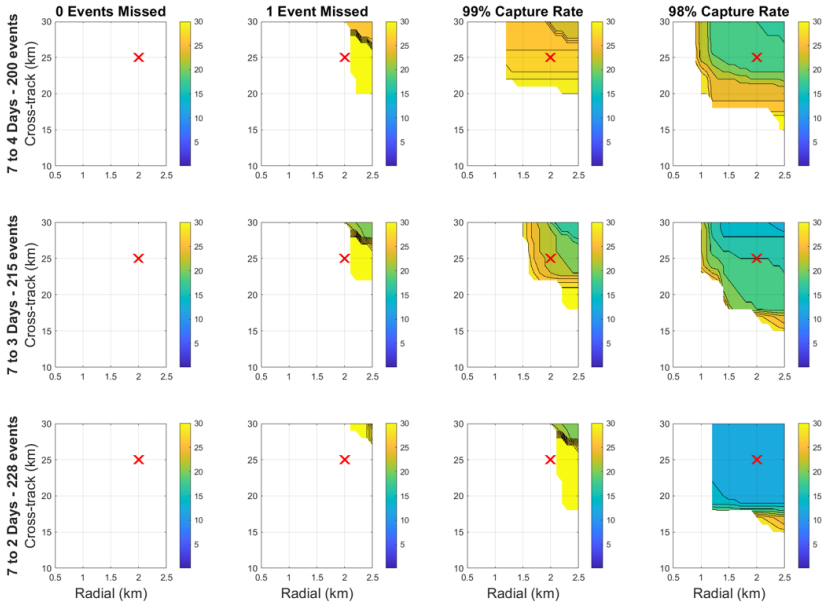

Fig. 9: Performance frontiers for the LEO-3 SV.

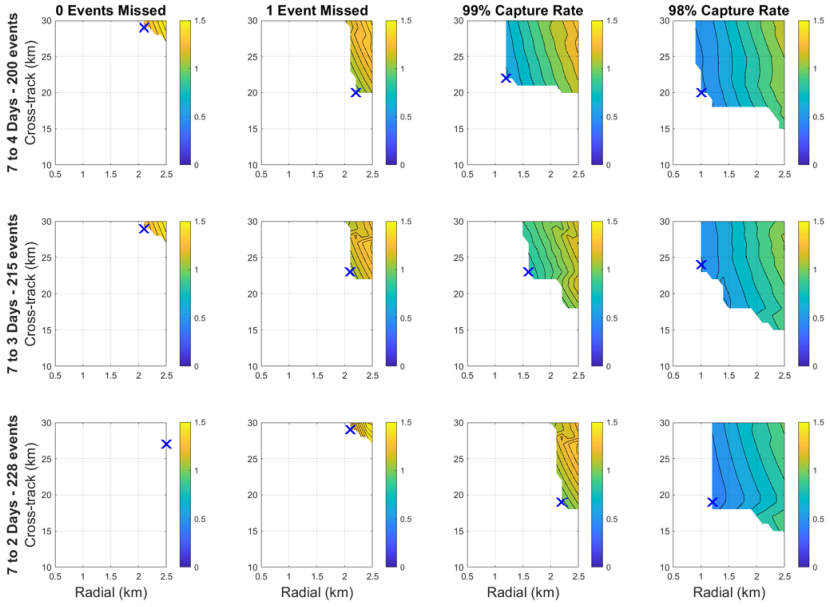

Fig. 10: Ratios of CDMs processed by frontier SVs to CDMs processed by the nominal LEO-3 SV

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4.1.4 LEO-4

Fig. 11 shows the performance frontiers for the LEO-4 SV study. Corresponding ratios of CDMs processed are shown in fig. 12. Note that due to the lower population in this regime, only 24 actionable red events were detected over 4 years of screening.

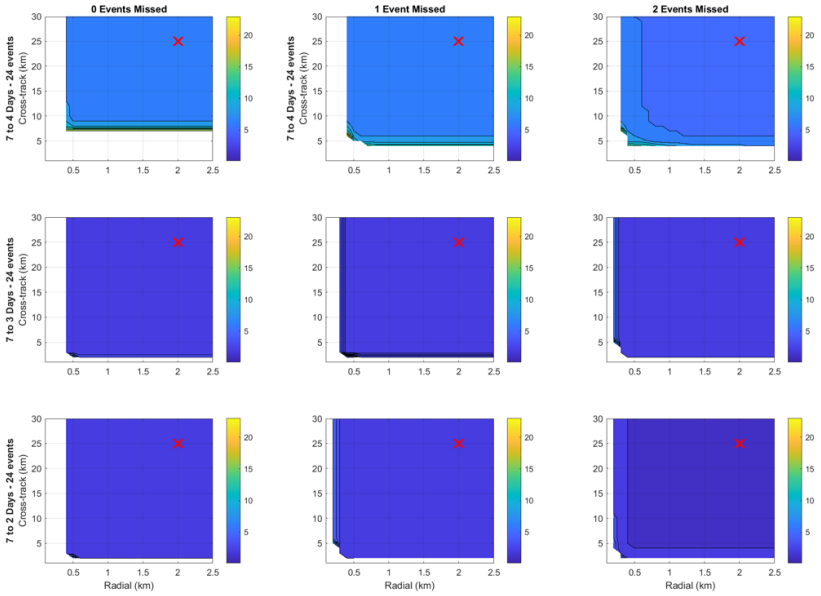

Fig. 11: Performance frontiers for the LEO-4 SV.

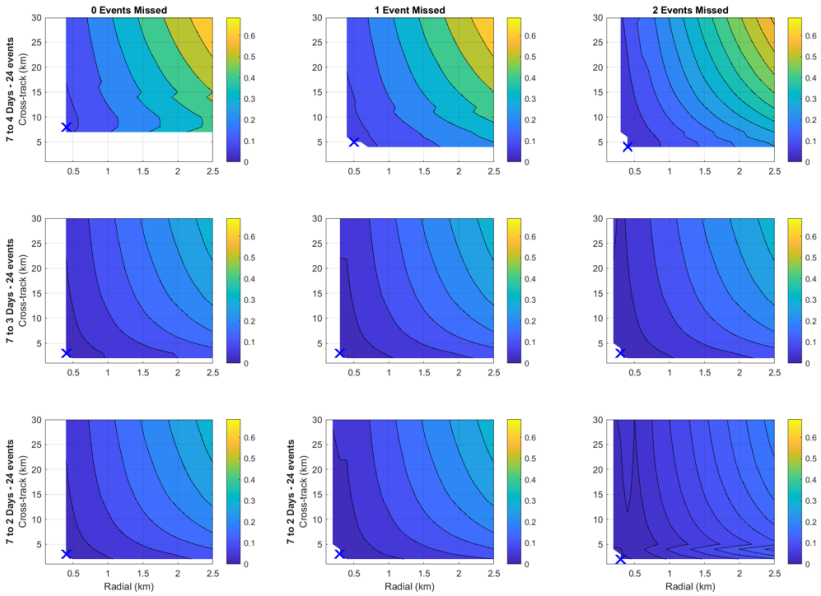

Fig. 12: Ratios of CDMs processed by frontier SVs to CDMs processed by the nominal LEO-4 SV

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4.1.5 HEO

Fig. 13 shows the performance frontiers for the HEO SV study. Corresponding ratios of CDMs processed are shown in fig. 14. The frontiers for the 7-2 day detection-commit window are significantly larger than the frontiers for shorter windows, suggesting that detection of actionable red events in the HEO regime is heavily dependent on data received very close to TCA.

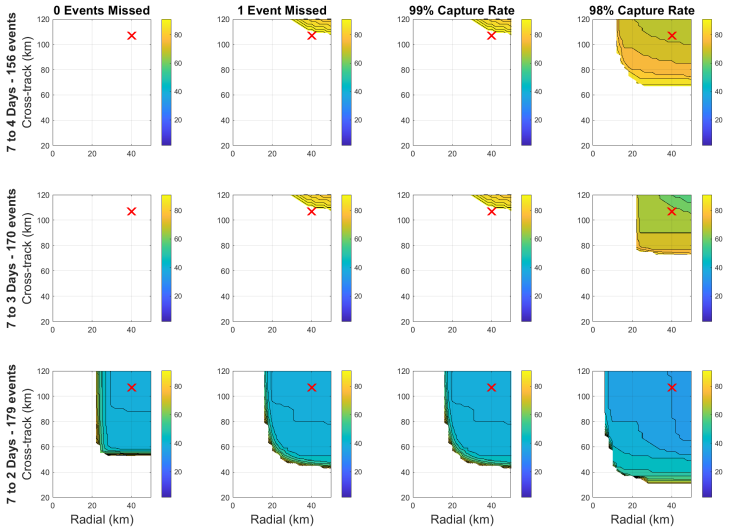

Fig. 13: Performance frontiers for the LEO-4 SV.

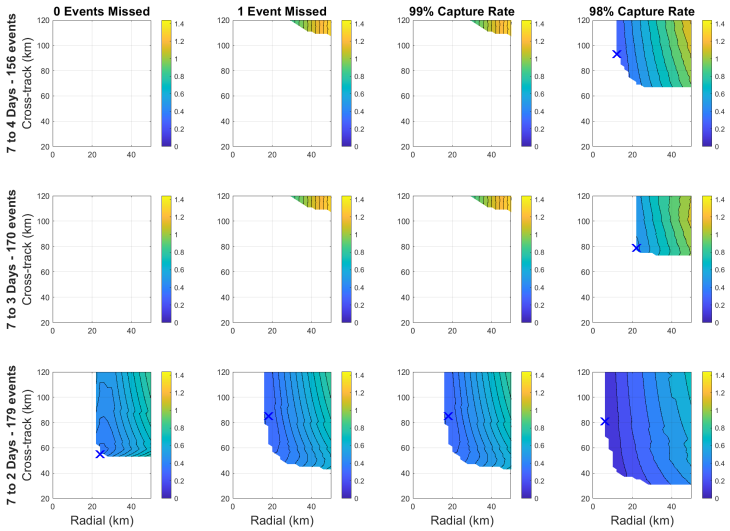

Fig. 14: Ratios of CDMs processed by frontier SVs to CDMs processed by the nominal LEO-4 SV

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4.1.6 DS/GEO

Fig. 15 shows the performance frontiers for the DS/GEO SV study. Corresponding ratios of CDMs processed are shown in fig. 16. These frontiers indicate significant room for reductions in all directions, regardless of the detection window or performance metric used. CDMs processed can be reduced by over 90%, even if dimensions are not reduced completely to the frontier.

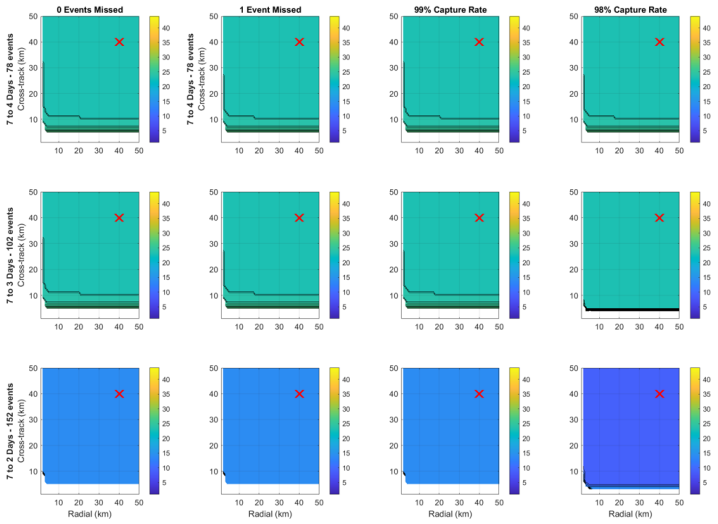

Fig. 15: Performance frontiers for the LEO-4 SV.

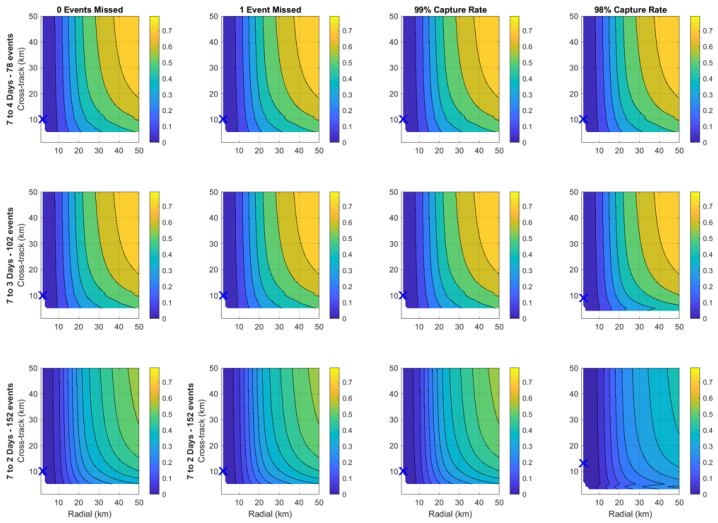

Fig. 16: Ratios of CDMs processed by frontier SVs to CDMs processed by the nominal LEO-4 SV

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4.1.7 Summary

Tab. 3 lists the SVs with the greatest achievable reduction in CDMs processed along with our recommended SV sizes. The optimal dimensions are based on the 98% performance frontier, which as we discussed earlier is a better performance metric to deal with outliers induced by HBR inflation. The recommended dimensions were obtained by rounding the optimal dimensions up to nearby round numbers, which provides additional safety margin.

Table 3: Recommended SV Sizes

Regime	Nominal Dimensions (km)	Optimal Dimensions (km)	CDMs (% of Nom.)	Rounded Dimensions (km)	CDMs % of Nom.
LEO-1	2 x 44 x 51	0.9 x 50 x 55	50.1	1 x 50 x 55	55.6
LEO-2	2 x 25 x 25	0.8 x 30 x 25	42.9	1 x 30 x 30	60.1
LEO-3	2 x 25 x 25	1 x 25 x 24	48.7	1 x 30 x 25	53.3
LEO-4	2 x 25 x 25	0.3 x 5 x 5	1.9	0.5 x 5 x 5	5.1
HEO	40 x 77 x 107	22 x 79 x 79	47.2	30 x 85 x 85	69.0
DS/GEO	40 x 40 x 40	2 x 23 x 10	2.2	5 x 25 x 15	5.4

4.2 TraCSS Screening Volumes

We also analyzed SVs being proposed for use by OSC in the TraCSS system. These SVs, listed in Tab. 4, are smaller than the corresponding NASA CARA SVs and also use different screening periods of 5 days in LEO and 10 days in DS/GEO (as opposed to the 7 days used by NASA CARA in all regimes.) There is no HEO regime SV analysis as OSC is not employing a separate SV for that regime.

Table 4: Proposed TraCSS orbital regimes and SV sizes

Regime	Perigee Altitude (km)	Eccentricity	SV RIC dimensions (km)	Screening period (days)
LEO-1	< 500	< 0.25	0.4 x 44 x 51	5
LEO-2	$500 - 750$	< 0.25	0.4 x 25 x 25	5
LEO-3	$750 - 1200$	< 0.25	0.4 x 12 x 12	5
LEO-4	$1200 - 2000$	< 0.25	0.4 x 2 x 2	5
GEO/DS	-	< 0.25	10 x 10 x 10	10

4.2.1 TraCSS LEO-1

Fig. 17 shows the performance frontiers for the LEO-1 SV study. For this study, we looked at lower performance thresholds of 98/95/90% capture rate. The 95% capture rate frontier extends slightly beyond the proposed SV for some detection windows while the stricter 98% frontier sometimes does not reach the proposed SV. Even in the longest detection window where the red 'X' is on the frontier edge, the required in-track distance to achieve a 98% capture rate is 50 km, higher than the current nominal in-track length of 44 km. Based on these results, the proposed SVs could be expected to achieve a capture rate between 95-98%, which may be treated as optimal given the effects of HBR inflation.

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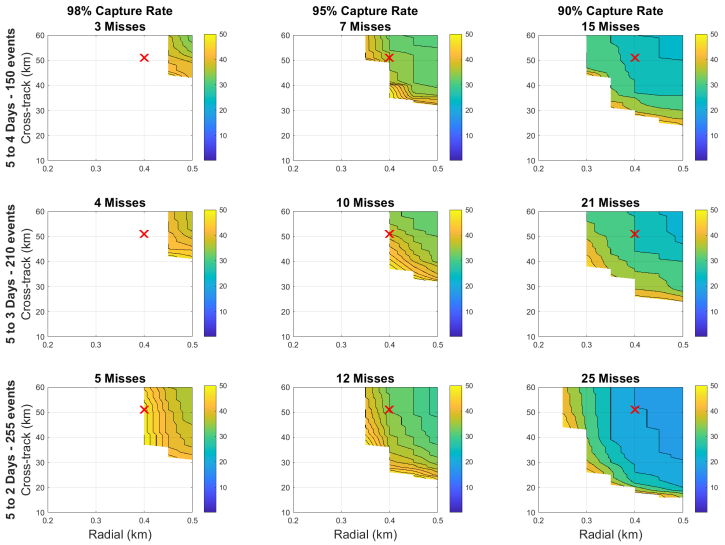

Fig. 17: 98/95/90% Performance frontiers for the LEO-1 SV. The nominal SV radial/cross-track dimensions are marked with a red X.

4.2.2 TraCSS LEO-2

Fig. 18 shows the performance frontiers for the LEO-2 SV study. Similarly to the LEO-1 results, the current nominal SVs are on the edge of the 95% capture rate frontiers but slightly beyond the reach of the 98% frontiers.

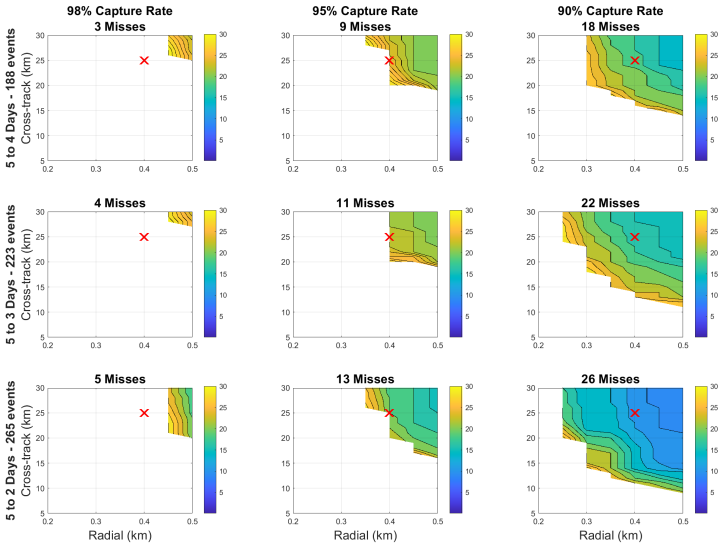

Fig. 18: 98/95/90% Performance frontiers for the LEO-2 SV. The nominal SV radial/cross-track dimensions are marked with a red X.

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4.2.3 TraCSS LEO-3

Fig. 19 shows the performance frontiers for the LEO-3 SV study. Again, the proposed SVs are right on the 95% frontier and very close to the 98% frontier.

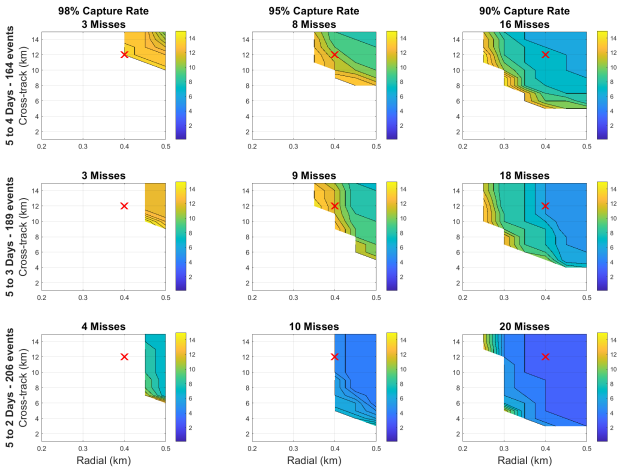

Fig. 19: 98/95/90% Performance frontiers for the LEO-3 SV. The nominal SV radial/cross-track dimensions are marked with a red X.

4.2.4 TraCSS LEO-4

Fig. 20 shows the performance frontiers for the LEO-4 SV study. The number of test events is very low due to the lower population and spatial density in this regime. Note that because 98/95/90% capture rate thresholds would not be useful at this low sample size, we instead show 0/1/2 events missed thresholds. While the frontiers suggest that the current nominal SV should be increased, we consider the sample size to be too low to draw a firm conclusion.

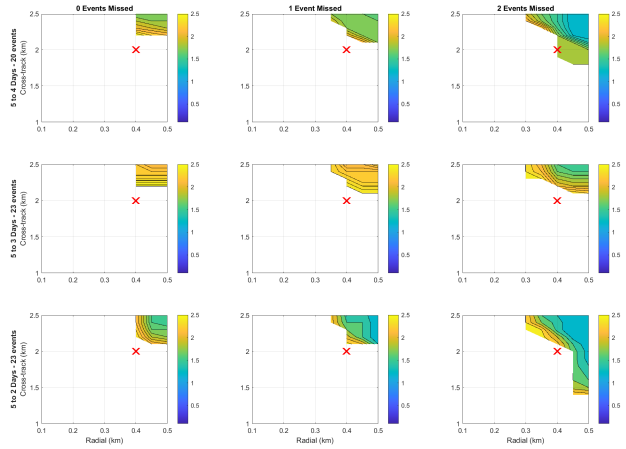

Fig. 20: 0/1/2 events missed performance frontiers for the LEO-4 SV. The nominal SV radial/cross-track dimensions are marked with a red X.

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4.2.5 TraCSS DS

Fig. 21 shows the performance frontiers for the DS/GEO SV trade study. The 98% frontiers suggest that SVs could be reduced to roughly 6x6x6 km without compromising detection rate, except for the test case including events detected 2-3 days before TCA which is also the largest test case. This frontier suggests that while the RC dimensions could be slightly decreased, the in-track dimension should be slightly increased. The 95% frontier plot suggests that an in-track direction of only roughly 7 km is necessary, so we can reason the proposed 10 km in-track direction to achieve somewhere between a 95-98% detection rate, or 3-8 events missed among 1,900 primaries over 4 years. Keep in mind that no HBR inflation effects were applied to the DS/GEO primaries, so performance is not affected by the existence of unnaturally long-distance red events.

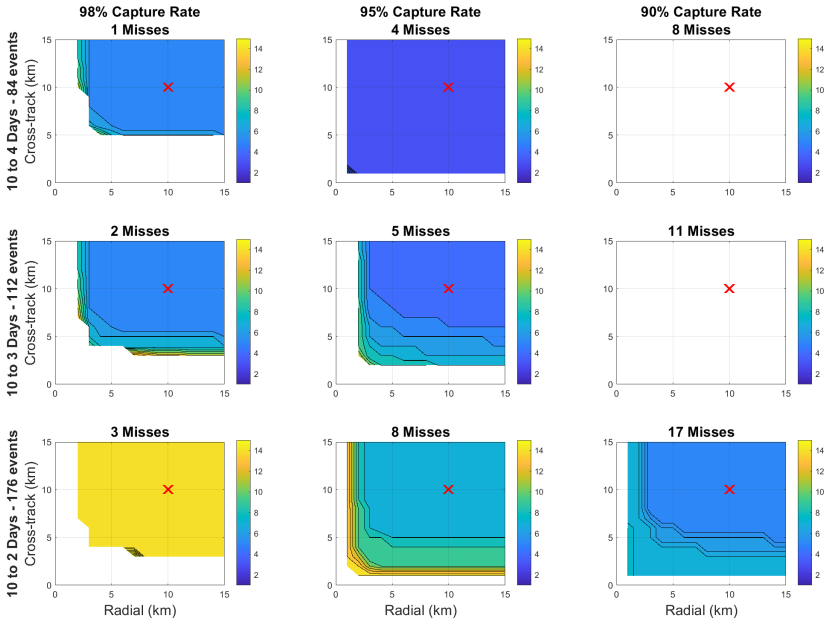

Fig. 21: 98/95/90% Performance frontiers for the DS/GEO SV. The nominal SV radial/cross-track dimensions are marked with a red X. Note that due to software limitations, some 90% performance frontiers appear blank when they are actually constant level throughout the entire test region.

5. CONCLUSIONS

In this paper, we evaluated screening volumes currently used by NASA and proposed for use by OSC based on their detection rates of actionable red events and computational efficiency. This was done using simulated conjunction data based on historical satellite catalogs over the course of four years. HBR inflation was applied in order to increase the presence of red events in a computationally feasible manner. The analysis was performed using multiple detection windows as maneuver commit times can vary amongst different operators. Our results showed that NASA CARA could adopt smaller SVs and reduce the number of CDMs processed by roughly 50% in LEO/HEO and over 90% in DS/GEO without compromising current red event detection rates. Additionally, we demonstrated that the LEO SVs being proposed by OSC were already very close to their optimal frontiers.

In the future, it may be worthwhile to repeat this study without using HBR inflation to increase the set of red events. The population of red events could be increased more naturally by screening more primaries and by doing three daily screenings, which would be consistent with current procedures. This would be especially useful for the LEO-4 regime, where sample sizes were too low to draw confident conclusions.

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6. ACKNOWLEDGEMENTS

This work was funded by the NASA CARA program and the Office of Space Commerce as part of the TraCSS program.

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